WATER AND NUTRIENT MOVEMENT IN TWO TROPICAL CROPPING SYSTEMS

By

MARK S. SEYFRIED

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Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Mark S. Seyfried

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Soil-water and nutrient movement in two contrasting cropping systems was compared to investigate the effect of cropping system management on leaching losses under humid tropical conditions. One cropping system, the monocropped annual, consisted of maize (Zea mays L.) alone; the other, mixed perennial system, consisted of cacao (Theobroma cacao), laurel (Cordia alliodora), and plantain (Musa paradisiaca) grown together. A model was developed to calculate nutrient leaching losses given measured soil solution concentrations. Displacement through undisturbed soil columns was used to select a modeling approach. The contribution of mineralized soil N was studied in incubation chambers.

Miscible displacement studies indicated that nutrient movement was well described by the convective-dispersive model except when the soil was at or very near saturation. Saturated hydraulic conductivity values measured in the

field were considerably higher than rainfall intensities, suggesting that preferential flow conditions were very rare. A zero-order kinetic model, with consideration made for pretreatment effects, was shown to describe the measured N mineralization rates well. These results appear to apply to a variety of soils.

The simulation model used was based on soil-water capacity parameters. Piston displacement of solutes and drainage to field capacity were assumed.

Simulated profile soil-water contents closely approximated those measured. Calculated net leaching losses of N, K^+, Ca^{2+} and Mg^{2+} were greater in the monocropped annual system due mainly to differences in soil solution concentrations, which were constant over time. The calculated loss of N from the monocropped plot was 56 kg ha^{-1} over 260 days. Losses from the mixed perennial plot were negligible.

The solute residence time within the crop root zone was proposed as an index of cropping system sensitivity to leaching loss. The residence time in the mixed perennial system was about 1.4 times larger in the monocropped system. The low leaching losses from the mixed perennial plot, in spite of substantial annual inputs of nutrients, indicates that that system is conservative in terms of nutrient use. This was attributed to the relatively long residence time in the rooting zone of the mixed perennial plot.

CHAPTER I
INTRODUCTION

The humid tropics, as defined by Sanchez et al. (1982), comprises about 10% of the earth's land surface. This region is currently undergoing very rapid ecologic, economic and social changes. These changes frequently require more intensive use of the land to produce food and fiber. This, in turn, requires changes in extant farming methods.

The traditional system of farming for much of the region, which is still used extensively, is commonly referred to as slash and burn agriculture or shifting cultivation. Although the details of operation are extremely variable, the basic pattern is fairly consistent throughout the world. First, the forest is felled and burned. Crops are then planted in the ash and 2 to 4 harvests follow. The land is then abandoned and crop production is shifted to a new site. Shifting is necessitated by the marked, rapid decline in crop production that almost invariably accompanies cropping. The abandoned land is left in fallow for 4 to 20 years after which time the process is repeated.

The success of the system is based on the restoration of soil productivity during the fallow period. If that period is sufficiently long, the system works in an ecologic sense (Sanchez, 1982). In much of the region, increasing populations, coupled with governmental encouragement, is

causing influxes of peasant farmers and increased demand for food. This, along with the desire to preserve some of this unique habitat, is forcing reduced fallow periods and consequent land degradation (Trenbath, 1984). These changes are forcing the development and adoption of agricultural techniques that are productive and can sustain continuous cultivation.

Several factors have been attributed to the observed yield declines with cropping. These include, declines in soil fertility, increased weed infestation, deterioration of soil physical properties, increased insect and disease attacks, and social customs (Sanchez, 1976).

Whatever the cause of yield declines may be, it is clear that, if sustained soil productivity is to be achieved, soil fertility must be maintained or enhanced. One way to achieve this is to add nutrients and other required inputs in sufficient quantities to overcome yield limitations. This approach has recently been adopted by industrialized (mostly temperate zone) nations. Sanchez et al. (1982) have shown that this approach can work in both an agronomic and economic sense in a humid tropical setting. The problem is that it requires a fairly well developed infrastructure that provides farmers with access to a wide variety of soil amendments, seed varieties and pesticides, sufficient capital and credit to purchase them, sufficient knowledge to properly manage them, and a well developed marketing and transportation system.

An alternative approach that has received considerable attention in recent years is based on the somewhat paradoxical observation that the land that supports some of the world's most productive natural ecosystems (tropical rainforest), supports some of the world's least productive agro-ecosystems. If cropping systems were developed that are more like the natural ecosystem, it is reasoned, they should be more productive. This reasoning is supported by the observation that most indigenous systems (excluding paddy rice) that are of semi-permanent nature, are somewhat like natural systems in that they are characterized by a variety of different crops, including tree species, grown together. The potential for designing such systems was demonstrated by Hart (1980), who carefully planted crops to mimic natural succession and obtained good, economic yields.

In practice it appears that few farmers are purists in terms of the approach they adopt. A wide variety of cropping systems and input levels are in use. In all cases, an important consideration is that plant nutrients in the soil be conserved. Low input systems will "run down" and high input systems will be prohibitively expensive if nutrient losses are high. One process that can cause nutrient losses is leaching.

Leaching in Humid Tropical Regions

The observed soil productivity decline under shifting agriculture has been attributed to leaching losses (Sanchez, 1976). Leaching is also considered to be a major factor

that limits the effectiveness of fertilizers in the region (Engelstad and Russel, 1975).

At the outset it should be pointed out that the processes involved in nutrient leaching in the tropical regions are the same as those in temperate regions. A given nutrient will be leached below the crop rooting zone when it moves through the soil faster than the crop can absorb it. This is dependent on the climate, soil and crop. Thus, the amount of a nutrient entering the soil solution and the rate at which it moves are important. Management practices, as well as the soil, climate, and crop, effect this. Since all of these factors are generally different in humid tropical regions, the magnitude of the problem is potentially different there than in temperate regions.

Rainfall is particularly noteworthy in this respect. In many humid tropical regions the mean annual rainfall exceeds 200 cm and, even though the potential evapotranspiration is also high, it is often exceeded considerably by rainfall. At Turrialba, Costa Rica, for example, rainfall exceeds the potential evapotranspiration by approximately 100 cm yr^{-1}, which is roughly equal to the average annual precipitation in most temperate agricultural regions.

Although generalizations about soils for such a large region are dangerous, there are some differences between soils of temperate and tropical regions that are common. In particular, soils in humid tropical regions frequently

exhibit infiltration rates much greater than those expected in temperate soils of similar clay content (Sanchez, 1976). This is generally attributed to the relatively high degree of aggregation commonly found in those soils. Since this characteristic obviously affects water movement, it also effects solute (nutrient) movement.

Another difference between soils is that the clay fraction of the soils in the humid tropics is commonly dominated by variable charged, low activity clays. This effects the retention of both cations and anions.

Finally, the differences in individual crop species and their management is frequently different from temperate crops and management. All of these factors combine to make transfer of agricultural experience and research in temperate regions to the humid tropics tenuous. This is certainly true of nutrient leaching studies.

Despite widespread concern that leaching may be an important constraint to soil productivity in the humid tropics, very little quantitative data have been reported in the literature (Greenland, 1977; Keeney, 1982; Omoti et al., 1983). This is partly because it is a difficult parameter to measure and partly because much of the research in the region is result-oriented (crop yield) as opposed to process-oriented.

Measurements that have been made range considerably. Amounts of N estimated to have been lost in a year, for example, range from 37 kg ha^{-1} (Omoti et al., 1983) under

oil palm, to 204 kg ha^{-1} from a pasture in Colombia (Sanchez, 1976). A recent study of leaching from maize in Nigeria calculated N losses to be about 80 kg ha^{-1} for a single fertilizer application of 150 kg ha^{-1} and approximately half that for a split application (Arora et al., 1982). Similar ranges of losses for K^+ and Mg^{2+}, and even greater ranges for Ca^{2+}, have been reported (Sanchez, 1976).

Objectives

At present it seems clear that there is a high potential for nutrient leaching losses in humid tropical regions. It is also clear that research into management systems that minimize such losses is an important priority. It has been proposed that cropping systems can be manipulated in such a way that such losses can be minimized. The principal objective of this study was to establish if nutrient losses from two different cropping systems, which are strongly contrasted in terms of species composition and diversity, are different when levels of management are similar.

The fact that such wide ranges in leaching losses are reported in the literature indicates that the processes responsible for leaching must vary greatly in the region. A second, related objective, was to quantify the processes responsible for leaching in such a way that the sensitivity of cropping systems can be characterized.

Setting

The two cropping systems chosen for comparison were: (1) a mixed cropping system composed of laurel (Cordia

alliodora), cacao (Theobroma cacao) and platano (Musa paradisiaca), and (2), a monocropping system composed of maize (Zea mays L.). These two cropping systems will be referred to as the MP, for mixed perennial, and MA, for monocropped annual, in the remainder of the dissertation.

The two cropping systems were separated by approximately 100 m and were located in the "La Montaña" section of the experimental plots at CATIE (Centro Agronomico de Investigaciones y Ensenanzas) near Turrialba, Costa Rica. The soil series for both systems is Instituto clay loam which is classified as a Typic Dystropept, fine, mixed, isohyperthermic (Aguirre, 1971).

The management level of both systems was designed to promote high yields and profitability. The MA plot is located in a larger study area used by Dr. Carlos Burgos to study the effects of tillage and residue management on maize yields. It was initiated in November of 1976. Since then 40,000 plants ha^{-1} of a 120-day maize variety have received approximately 400, 55, and 40 kg ha^{-1} of N, P, and K, respectively, each year in four applications. Two crops were grown each year. The dimensions of the plot discussed in this study were 32 by 20 m.

The MP plot was part of a larger study of intercropping with perennials directed by Dr. Gustavo Enriquez. It was initiated in 1977. The planting densities were 1,111; 432; and 123 plants per hectare for cacao, laurel, and platano, respectively. The annual fertilizer regime was 140 kg ha^{-1}

N, 30 kg ha^{-1} P, and 20 kg ha^{-1} K in four applications. The dimensions of the MP plot were 18 by 18 m.

Presentation

Three lines of inquiry, connected to the basic theme of nutrient movement under the two cropping systems will be presented in three separate chapters. First, investigations of the nature of solute flow through the soil at the site will be presented. This work was performed to establish the appropriate model to be used in estimating field-scale water and solute movement at the site.

The second line of inquiry is devoted to the development and implementation of a soil-water and nutrient movement model that was used to estimate leaching losses and examine critical parameters associated with those losses.

The third line of inquiry is related to the supply of nutrients to the systems via mineralization of soil organic matter. In this section a laboratory method for estimation of N mineralization is examined in terms of three models. Implications of the results to field application of incubation results is also discussed.

The results presented in the three chapters are summarized and discussed in terms of implications to the functioning of the two cropping systems in the final chapter.

CHAPTER II
PATTERNS OF SOLUTE MOVEMENT

Introduction

This study is part of a larger project investigating nutrient movement under different cropping systems in Costa Rica. Throughout the humid tropics there is a high potential for loss of plant nutrients by leaching due to the considerable excess of precipitation over evaporative and transpirational demand. Near Turrialba, Costa Rica, where this study was performed, for example, the mean annual precipitation of 264 cm exceeds mean annual pan evaporation by 130 cm. Since improved crop yields are largely dependent upon increasing the nutrient status of soils in the region, quantification of leaching loss is important.

Quantitative description of solute (e.g., nutrient) transport through packed soil columns has been accomplished using the convective-dispersive (CD) model of solute flow (Kirkham and Powers, 1972). Verification of this model has come through numerous studies of miscible displacement through uniformly packed, sieved, water saturated columns of soil and other porous media (Nielsen and Biggar, 1961, 1962). According to the CD model, the transport of a non-adsorped, conservative solute under steady water flow conditions is described by

$$\partial C/\partial t = D\partial^2 C/\partial z^2 - v_o \partial C/\partial z \qquad (2\text{-}1)$$

where C is the solute concentration (mg cm^{-3}), z is distance (cm), t is time (hr), D is the "effective" dispersion coefficient (cm^2 hr^{-1}) and v_o is the average pore water velocity (cm hr^{-1}). The average pore-water velocity is calculated by dividing the Darcy-flux (q) by the soil water content Θ. This implies that all soil water participates in the convective transport of the solute.

In working with packed soil columns under steady water flow conditions, two experimental conditions in which the CD model has failed are (1) when aggregated media are used (Nielsen and Biggar, 1961; Green et al., 1972), and (2) when displacement was conducted under unsaturated conditions (Biggar and Nielsen, 1962; Gupta et al., 1973; Gaudet et al., 1977). In both cases this failure may be ascribed to a failure of the assumption that all soil-water participates in convective transport. When aggregated media are used, intra-aggregate water is essentially stagnant so that virtually all convective transport occurs in the mobile water located in the inter-aggregate portion of the soil. Similarly, the application of tension to the soil causes the entrance of gas which may result in the isolation of stagnant regions. Again, convective flux is restricted to the mobile, nonstagnant-region water and Eq. 2-1 is not applicable.

Application of miscible displacement techniques to "undisturbed" soil columns taken from the field have shown that inhomogeneities in field soils can strongly affect the

nature of water and solute flow (McMahon and Thomas, 1974; Cassel et al., 1975). The presence of macropores is often associated with solute flow behavior that is inconsistent with the CD model (Kanchanasut et al., 1978). At present no precise definition of macropores is widely accepted (Bouma, 1981; Luxmoore, 1981), but the term is generally used to describe large, continuous pores that can conduct water and solutes much more rapidly than the surrounding soil matrix (Bevin and German, 1982; White, 1985). The process of flow along macropores has been variously described as "channeling", "bypassing", "short circuiting", "preferential flow" or "partial displacement" (Scotter, 1978; Bouma, 1981; Beven and German, 1982; Thomas and Phillips, 1979). The term bypassing will be used in this paper.

The presence of relatively few macropores can greatly increase the soil hydraulic conductivity (Bouma and Anderson, 1973) and cause very rapid transport of solutes through the soil (Thomas and Phillips, 1979; Bouma et al., 1982) that is inconsistent with the CD model (Kanchanasut et al., 1978). The average pore water velocity (v_o) is not an appropriate descriptor of convective transport when there is bypassing because flux is effectively limited to a small portion of the total soil-water (i.e., that within macropores).

Application of Eq. 2-1 on a field-plot scale has shown that the parameters v_o and D are extremely variable and log-normally distributed (Biggar and Nielsen, 1976), which

makes their estimation very difficult. Application of numerical models, which have been developed for more realistic, transient conditions that exist in the field, are subject to similar limitations.

As an alternative, management level models that use less variable, capacity-type parameters (e.g., Θ) have proven successful in many cases (Rao et al., 1981; Rose et al., 1982). These models are largely empirical in nature but utilize the concept of convective transport, as defined by v_o. Failure of these simplified management level models has been attributed to flow along macropores (Thomas and Phillips, 1979; Barry et al., 1985).

The three situations mentioned above in which the inapplicability of Eq. 2-1 have been documented; unsaturated flow; flow around aggregates; and flow along macropores, have in common the fact that a portion of the soil-water, called mobile water (Θ_m) in this paper, moves much more rapidly through the soil than the remaining, immobile water (Θ_{im}). Surface applied solutes can be transported much more rapidly in the mobile region and thereby bypass solutes residing in immobile regions.

An alternative model, known as the mobile-immobile water model (MIM) has been developed to explicitly account for this situation (Passioura, 1971; Van Genuchten and Wierenga, 1976). In this model two soil-water phases are explicitly differentiated, with all convective transport assumed to occur in the mobile phase and transport in the

immobile phase restricted to diffusion. Since no specific pore geometry is assumed, the diffusive transfer between the two soil-water phases is described as being proportional to the concentration difference between them. The equation for transport of a nonadsorped solute under steady water flow conditions that is consistent with the MIM model is

$$\Theta_m \partial C/\partial t + \Theta_{im} \partial C_{im}/\partial t = D\partial^2 C_m/\partial z^2 - \Theta_m v_m \partial C/\partial z \qquad (2\text{-}2)$$

with interphase transfer described as

$$\Theta_{im} \partial C_{im}/\partial t = \alpha(C_m - C_{im}) \qquad (2\text{-}3)$$

where the subscripts "m" and "im" refer to mobile and immobile phases, respectively. The parameter α is an empirical constant called the mass transfer coefficient (hr^{-1}). The parameter v_m differs from v_o in that it is calculated from q/Θ_m. Simplified, capacity-parameter based management level models, analogous to those based on the CD model, have been developed for the MIM model (Addiscott, 1977). Use of this model requires the fraction of mobile water Φ (Θ_m/Θ), as an input.

Our primary objective in this study was to select a modeling approach to describe water and solute movement under field conditions. From the above discussion it is clear that the nature of the conducting pore network, or the hydrologically effective pore geometry, greatly affects the applicability of a given model. Ideally, it would be possible to infer which model (if either) is appropriate from standard soil descriptions. Although the impact of soil structure on the hydrologically effective pore geometry

is well documented (Elrick and French, 1966; Cassel et al., 1974; McMahon and Thomas, 1974), and the effects of soil texture are widely recognized (Thomas and Phillips, 1979; Addiscott and Wagenet, 1985), the information is of a qualitative nature (Bouma, 1981). More detailed morphological descriptions are generally not well suited to this purpose because they do not yield information on pore continuity or the degree of pore interconnections (Bouma, 1981). For these reasons, study of the hydrologically effective pore geometry has usually focused on measurements of soil hydraulic properties (Bouma and Anderson, 1973) and movement of tracers (Bouma, 1981; White, 1985).

Our secondary objective was to identify soil structural or pore characteristics that characterize the hydrologically effective pore geometry. This information is potentially useful in using field-level observations to infer the nature of flow through soils. Dyes have been used extensively for this purpose (Bouma and Dekker, 1978; Omoti and Wild, 1979).

Materials and Methods

Soil Characteristics and Management

The soil studied is an Instituto clay loam (fine-loamy, mixed, isohyperthermic, Typic Dystropept) located at CATIE (Centro Agricola Tropical de Investigaciones y Ensenanzas) near Turrialba, Costa Rica. It is derived from alluvium deposited from the surrounding mountains which are primarily of volcanic origin. Very little soil profile development

was evident except for an accumulation of organic matter at the surface. Textures are clay loam throughout. Aguirre (1971) described the structure as weak, subangular blocky with peds ranging from 0.5 to 2.0 cm in diameter near the surface and becoming increasingly less pronounced with depth. The site is nearly level and the soil is considered to be moderately well drained (Aguirre, 1971).

Soil columns were taken from two experimental plots located about 100 m apart. One plot had been planted to maize for six years prior to column removal. The crops on the other plot were a mixture of cacao, laurel, and plantain and had been under continuous management for five years prior to column removal. No tillage was performed on either plot during that time and no machinery entered either plot. Columns numbered 1, 2, and 3 (Table 2-1) were taken from the first plot and those numbered 4 and 5 were taken from the second.

Column Experiments

Five undisturbed soil columns were collected at two depths (0-30 cm and 75-105 cm). The procedure used to collect the samples was as follows: (1) dig a pit approximately 1.0 by 1.5 m leaving a pedestal approximately 0.3 m^2 in the middle, (2) cut a circle about 15 cm in diameter in the middle of the pedestal with a sharp knife, (3) force the 12 cm diameter PVC tube that is beveled at the end and lined with petroleum jelly into the area bounded by the circle, (4) shave the surrounding soil from the edges of the pipe

and cut another circle about 1 cm deep, (5) repeat the last two steps until the 30 cm long column is filled, and (6) separate the column from the soil at the bottom. The upper 12 to 15 cm of each column were used in the displacement experiments.

Fritted glass endplates were fitted to both the inlet and outlet ends of the columns. A constant hydraulic potential was maintained at both column ends during displacement experiments. Tension was applied at the inlet end via a Marriot devise and at the outlet end by a hanging water column. All displacement experiments were conducted under a unit hydraulic head gradient except the two displacements performed in Column 1 (Table 2-1) under saturated conditions. The influent ^{3}H activity was about 7 nCi ml^{-1} in a 0.01 M $CaCl_2$ solution. The ^{3}H activity in effluent fractions was assayed using liquid scintillation techniques.

Rhodamine B dye displacements were performed using the same columns after the $^{3}H_2O$ displacements. The influent dye concentration was 2 g L^{-1}. The amount of dye displaced ranged from 0.05 to 0.32 pore volumes (Table 2-1). Dye patterns in cross-sections of the columns were photographed at 1 cm intervals after displacement. Selected cross-sections were then traced with pen and ink.

The experimental conditions under which all displacements were performed are summarized in Table 2-1.

Table 2-1. Experimental conditions for displacement.

Column Number	Column Length	Depth	Tension of ^3H Displ.	Tension of Dye Displ.	Pore Vol. Displ.*
	cm		---------kPa----------		
1	12.5	surface	0.0,0.1,0.5, 1.0,2.0	1.0	0.32
2	15.0	subsoil	0.0,1.0	0.0	0.05
3	12.5	surface	0.0,1.0	0.0	0.13
4	12.0	subsoil	0.0,1.0	1.0	0.19
5	12.5	surface	0.0,1.0	---	

* The number of pore volumes displaced during the dye application.

Field Techniques

The depth to the water table was measured in perforated, 2.54 cm diameter PVC pipe. Measurements were made several times each week. Rainfall was measured daily at the site. Infiltration measurements, carried out under the direction of Dr. Carlos Burgos, were made with a double-ring infiltrometer at 24 locations on an adjacent plot. The dimensions of the inner and outer rings were 31 and 60 cm, respectively.

Adsorption Experiments

Adsorption of ^3H_2O was measured using two different batch techniques under two slightly different conditions. The first method was that described by Dao and Lavy (1978) in which the soil-solution ratio was 2 to 1 (g g^{-1}). The soil used was taken from column 3 after the displacement experiments had been performed and the soil was oven dried for pore volume determination.

In the second method, air-dried soil from column 3 but not used in the displacement experiment, was added to ^3H_2O solution in a soil-solution ratio of 1 to 2 and placed in a

shaker overnight. Concentrations of ^3H_2O ranged from 7 to 0.7 nCi ml^{-1} in both experiments.

Parameter Estimation and Model Evaluation

In Eqs. 2-1 through 2-3 no adsorption was assumed, which is unrealistic for most tracers. Expansion of Eq. 2-1 to include adsorption results in the following expression:

$$\partial C/\partial t + (BD/\Theta)(\partial S/\partial t) = D\,\partial^2 C/\partial z^2 - v_o \partial C/\partial z \qquad (2\text{-}4)$$

where BD is the bulk density (g/cm^3), S is the adsorbed phase concentration (mg g^{-1}) and the other parameters have been previously defined.

Adsorption can frequently be described by a linear (or linearized) equation of the form

$$S = K_D C_e \qquad (2\text{-}5)$$

where C_e is the equilibrium solution concentration (mg cm^{-3}) and K_D is an empirical distribution coefficient (g cm^{-3}). If the adsorption process is assumed to be instantaneous and reversible, Eq. 2-5 can be substituted into Eq. 2-4 to give

$$RF\,\partial C/\partial t = D\partial^2 C/\partial z^2 - v_o \partial C/\partial z \qquad (2\text{-}6)$$

where RF, the retardation factor, is defined by

$$RF = 1 + BDK_D/\Theta. \qquad (2\text{-}7)$$

Analysis and interpretation of parameter values is facilitated by the use of dimensionless variables. Equation 2-6 can be described in terms of the following dimensionless variables:

$$T = v_o t/L, \qquad (2\text{-}8)$$

$$x = z/L, \qquad (2\text{-}9)$$

$$P = v_o L/D, \text{ and} \qquad (2\text{-}10)$$

$$C = C_b/C_o, \qquad (2\text{-}11)$$

where v_o, t, z and D have been defined previously, L is the column length, P is the Peclet number, T is the number of pore volumes, x the dimensionless distance, and C the ratio of effluent (C_b) to influent (C_o) concentration. (Note that the initial soil solution concentration is assumed to be 0). Substitution of these variables into Eq. 2-6 results in the following expression:

$$RF(\partial C/\partial T) = (1/P)(\partial^2 C/\partial x^2) - \partial C/\partial x. \qquad (2\text{-}12)$$

In order to incorporate adsorption into Eqs. 2-2 and 2-3, S is partitioned between mobile and immobile phases such that

$$S = fS_m + (1-f)S_{im} \qquad (2\text{-}13)$$

where S_m and S_{im} are the adsorbed concentrations in the mobile and immobile regions, respectively, and f is the fraction of adsorption sites in the mobile region. Assuming that the same linear relationship expressed in Eq. 2-5 applies to both the mobile and immobile regions, Eqs. 2-2 and 2-3 can be written

$$(\Theta_m+BDfK_D)\partial C_m/\partial t + [\Theta_{im} + (1-f)BDK_D]\partial C_{im}/\partial t = (\Theta_m D)\partial^2 C_m/\partial x^2 - (\Theta_m v_m)\partial C_m/\partial x \qquad (2\text{-}14)$$

and

$$[\Theta_{im}+(1-f)RoK_D]\partial C_{im}/\partial t = \alpha(C_m-C_{im}). \qquad (2\text{-}15)$$

As with the CD model, the MIM model can be described in terms of dimensionless variables. The variables used are

$$\beta = (\Theta_m + fBDK_D)/(\Theta + BDK_D), \qquad (2\text{-}16)$$

$$w = \alpha L/q, \qquad (2\text{-}17)$$

$$c_1 = C_m/C_o, \text{ and} \quad (2\text{-}18)$$

$$c_2 = C_{im}/C_o, \quad (2\text{-}19)$$

where c_m and C_{im} refer to soil solution concentrations in the mobile and immobile regions. All other parameters have been defined previously. The MIM model for steady-state water flow conditions can now be described by

$$\beta RF(\partial c_1/\partial T) + (1-\beta)RF\partial c_1/\partial T = (1/P)(\partial^2 c_1/\partial x^2) - \partial c_1/\partial x \quad (2\text{-}20)$$

and

$$(1-\beta)RF\partial c_2/\partial T = w(c_1-c_2). \quad (2\text{-}21)$$

The result of these transformations is that the CD model is described by Eq. 2-12 and the MIM model by Eqs. 2-20 and 2-21. Measured solute breakthrough curves (BTC's) were fit to both the CD and MIM models. The program CFITIM (van Genuchten, 1981), which uses a nonlinear, least sum of squares criteria for goodness-of-fit was used. In every case a first type, constant concentration, influent end boundary condition was assumed. The other boundary condition was that of a semi-infinite column.

Results and Discussion

Hydraulic Parameters

The Darcy flux (q, cm hr^{-1}), soil-water content (Θ, cm^3 cm^{-3}), and soil-water tension (h, kPa) under which the experiments were performed are shown in Figs. 2-1 through 2-5. The hydraulic conductivity (K, cm hr^{-1}) value is included for the two BTC's in which K was not equal to q.

Hydraulic conductivity values were extremely high considering that the soil has a clay content of greater than 30%. The combination of high clay content and high saturated hydraulic conductivity (K_{sat}) is frequently indicative of flow along macropores (Bouma and Anderson, 1973; McKeague et al., 1982). Saturated Θ values are also fairly high.

A dramatic decrease (two orders of magnitude) in K was observed as h increased from 0 to 2 kPa (Fig. 2-1). This was accompanied by a relatively modest decrease (6.5%) in Θ. Similar trends in K and Θ were observed in the other columns (Figs. 2-2 to 2-5). This indicates either that: (1) few discrete, large (>0.5 mm radius) pores conduct large volumes of water rapidly under saturated conditions, or (2) water held in large pores serves to "connect" a number of pores that conduct water rapidly.

The series of tensions in Fig. 2-1 illustrates the transition between saturated and unsaturated conditions for the surface soil. Preliminary investigations with subsoil showed a qualitatively similar pattern. This similarity between subsoil and topsoil was confirmed in subsequent comparisons between saturated and unsaturated conditions (Figs. 2-2 through 2-5).

Qualitative Evaluation of Breakthrough Curves

In general, BTC shapes changed dramatically as soil water tension was increased. BTC's obtained under saturated conditions were highly skewed, characterized by very early

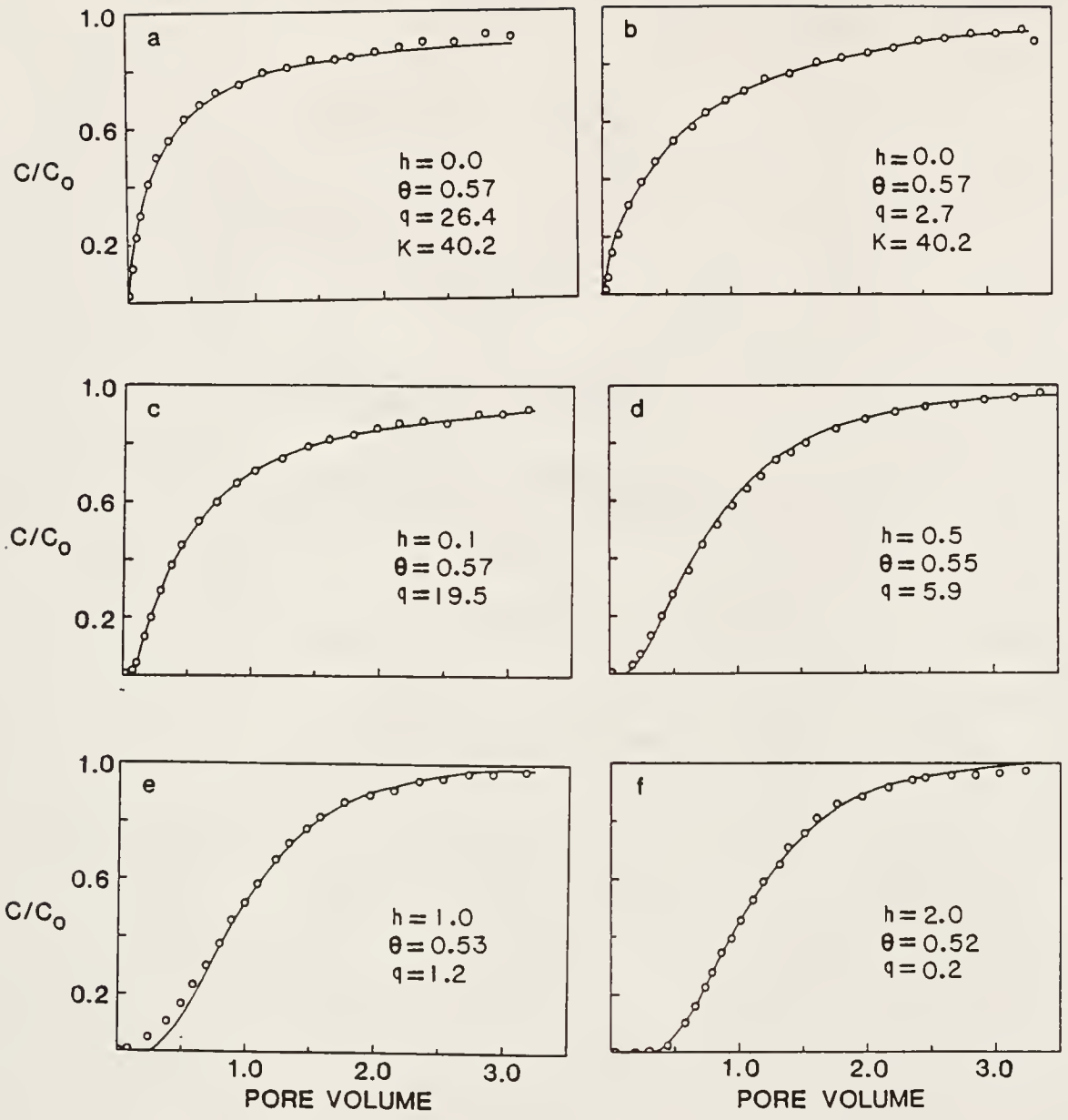

Figure 2-1, a-f. The effect of soil-water tension (h, kPa), soil-water content (Θ, $cm^3\ cm^{-3}$), and Darcy flux (q, $cm\ hr^{-1}$) on the elution of tritiated water in Column 1. The continuous line represents the best fit of the MIM model in a, b, and c, and of the CD model in d, e, and f.

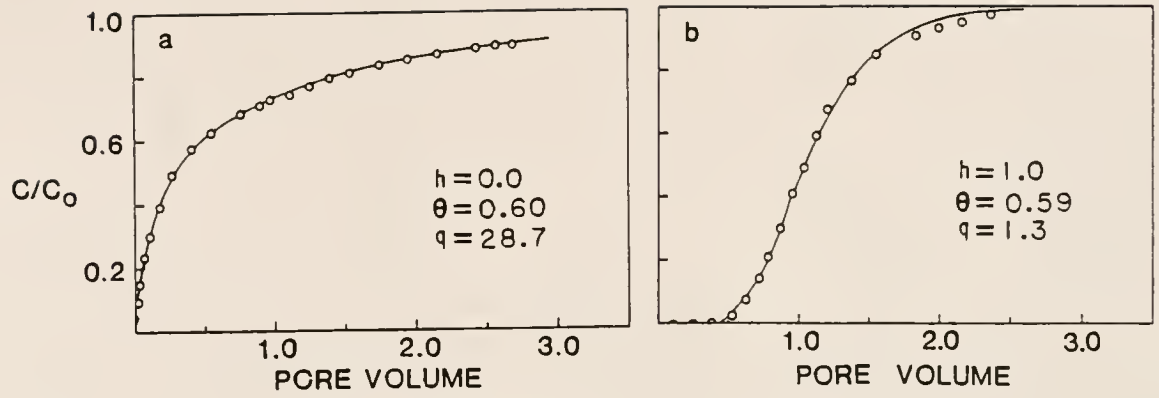

Figure 2-2, a and b. Effect of soil-water tension (h, kPa), soil-water content (Θ, $cm^3\ cm^{-3}$), and Darcy flux ($cm\ hr^{-1}$) on elution of tritiated water in Column 2. The solid lines in a and b represent the best fit of the MIM and CD models, respectively.

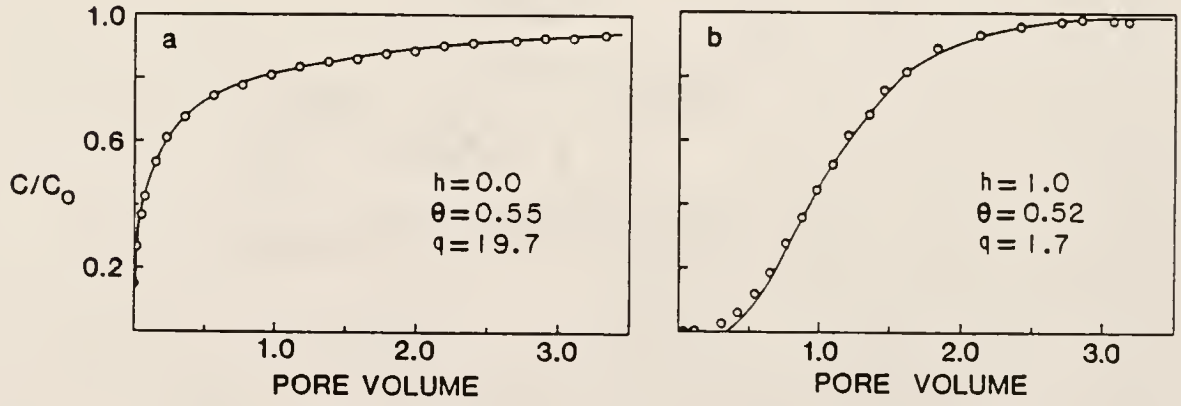

Figure 2-3, a and b. The effect of soil-water tension (h, kPa), soil-water content (Θ, $cm^3\ cm^{-3}$), and Darcy flux (q, $cm\ hr^{-1}$) on elution of tritiated water in Column 3. The solid lines in a and b represent the best fit of the MIM and CD models, respectively.

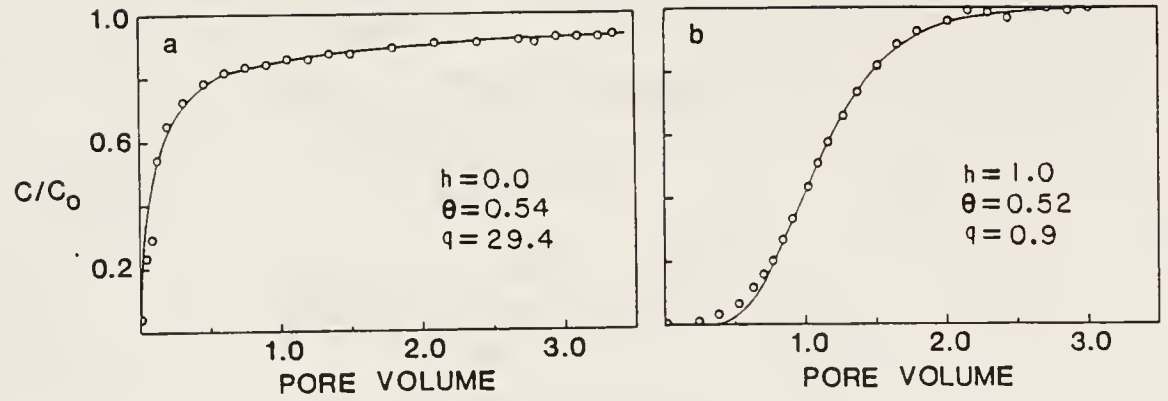

Figure 2-4, a and b. The effect of soil-water tension (h, kPa), soil-water content (Θ, $cm^3\ cm^{-3}$), and Darcy flux (q, $cm\ hr^{-1}$) on elution of tritiated water in Column 4. The solid lines represent the best fit of the MIM and CD models in a and b, respectively.

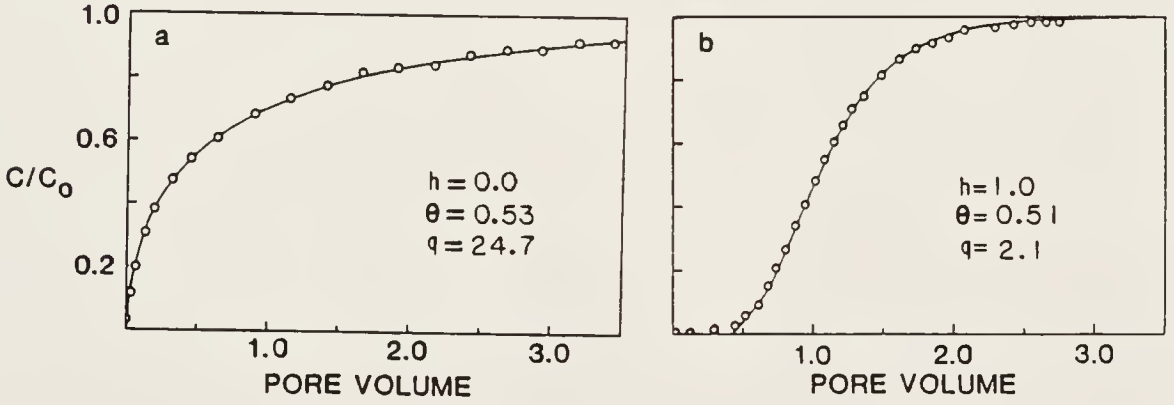

Figure 2-5, a and b. The effect of soil-water tension (h, kPa), soil-water content (Θ, $cm^3\ cm^{-3}$), and Darcy flux (q, $cm\ hr^{-1}$) on the elution of tritiated water in Column 5. The solid lines represent the best fit of the MIM and CD models in a and b, respectively.

appearance of tracer in the effluent and a slow approach of effluent concentration towards 1.0 (also called "tailing"). This behavior has been observed in undisturbed columns (Anderson and Bouma, 1977; White et al., 1984), and has been inferred from field studies of solute movement (Wild and Babiker, 1976). Such skewed BTC's indicate that solute was conducted relatively rapidly through the columns by a small fraction of the total soil-water. The rapidly conducting fraction of the soil-water has been related to inter-aggregate regions (Nkedi-Kizza et al., 1982), inter-ped regions (Anderson and Bouma, 1977), and discrete macropores (Kanchanasut et al., 1978) in other soils.

Unsaturated BTC's are markedly more symmetric, with a later arrival of tracer and less tailing. This trend was not reversed as tension was increased to 2 kPa. These results contradict other studies that have shown that tailing in BTC's resulted from increases in soil water tension (Nielsen and Biggar, 1961; Gaudet et al., 1977). Apparently the pore network in this soil is sufficiently interconnected that drainage of large pores does not result in the isolation of stagnant regions in the column. It should be noted that both of the studies referenced above were performed on sands in packed columns at relatively low soil-water contents. Lower soil-water contents enhance the possibility of the creation of isolated, stagnant regions in the soil. One study by Elrick and French (1966) that compared saturated and unsaturated flow in an undisturbed

column found that dispersion decreased with application of tension, although marked asymmetry during saturated flow was not observed.

The observed change in BTC shape with increasing soil water tension can be explained by the concomitant decrease in q and/or by changes in the effective pore geometry. In general, bypassing is enhanced by greater fluxes at a given Θ because because there is less time for diffusive transfer into stagnant regions. At the same time, increasing tension changes the effective pore geometry by draining larger pores that may be responsible for the observed bypassing.

Both effects were operative in this study but the effect on the effective pore geometry was dominant. This is illustrated in Fig. 2-1. When flow rates were reduced and the soil remained saturated (Figs. 2-1a and b), the BTC shape was only slightly altered. However, when displacement on the same column was performed under unsaturated conditions at approximately the same q (Figs. 2-1b versus 2-1d and e), there was a considerable change in BTC shape. These trends were reflected in the models and parameters used to describe the BTC's.

Quantitative Evaluation of Breakthrough Curves

All BTC's were fit to both the MIM model and the CD models. In general, curve fits fell into two groups, saturated and unsaturated, with the 0.1 kPa run (Fig. 2-1c) intermediate. The parameter values obtained will be discussed by these groups.

Unsaturated Breakthrough Curves

Two dimensionless parameters are required in the CD model, P and RF. The best least sum of squares fit was obtained allowing both parameters to vary. The solid line in all the unsaturated BTC's except the 0.1 kPa run represent the calculated best fit using the CD model (Figs. 2-1 through 2-5). In general, the agreement was excellent. The resultant parameter values and associated 95% confidence intervals shown in Table 2-2 appear to be independent of the depth from which the columns were sampled. Peclet numbers (P) ranged from 3 to 12 and RF values from 1.12 to 1.17. Dispersion coefficients calculated from those P values were high relative to those measured in sieved, packed columns, but this is expected in undisturbed columns (McMahon and Thomas, 1974; Cassel et al., 1975). It indicates that there was a relatively wide range of pore water velocities within the column.

The RF values obtained were high considering that tritium is frequently assumed to be nonadsorped (RF=1.0). Tritium sorption has been noted by several workers (Mansell et al., 1973; Wierenga et al., 1975; Van de Pol et al., 1977; Nkedi-Kizza et al., 1982) and has been associated with hydroxyl exchange with clay lattice hydroxyls (Stewart, 1973).

As a check of the accuracy of RF values determined by curve-fitting, the area above the measured BTC was calculated for several of the unsaturated BTC's (Pandey and Gupta,

1984). The areas measured agreed closely with the RF values obtained by curve-fitting. Since the fit between calculated and measured curves was excellent in every case, this result confirms the finding of van Genuchten and Parker (1984) that mass balance is preserved with the solution and boundary conditions used.

Table 2-2. Convective-dispersive model parameter values.

Col No.	h	P	RF	K_D	D
	kPa			ml g^{-1}	cm^2 hr^{-1}
1	0.1	0.90 (0.02)*	1.08 (0.01)	0.031 (0.006)	492 (11.7)
1	0.5	2.28 (0.06)	1.10 (0.01)	0.043 (0.006)	60.9 (0.02)
1	1.0	4.45 (0.31)	1.12 (0.02)	0.053 (0.008)	6.44 (0.17)
1	2.0	6.62 (0.17)	1.17 (0.01)	0.069 (0.002)	0.58 (0.01)
2	1.0	13.5 (0.76)	1.12 (0.01)	0.062 (0.005)	2.52 (0.13)
3	1.0	13.1 (0.49)	1.18 (0.01)	0.080 (0.002)	3.78 (0.14)
4	1.0	12.2 (0.57)	1.16 (0.01)	0.071 (0.003)	1.65 (0.07)
5	1.0	7.01 (0.36)	1.18 (0.01)	0.079 (0.005)	5.81 (0.18)

* Numbers in parenthesis are the 95% confidence intervals associated with the estimated value.

An independent check of RF can be obtained from measurement of adsorption in batch isotherms. The batch isotherms obtained using both methods described in the previous section were essentially identical. Both isotherms were linear with r^2 values of 0.994 and 0.997 and K_D values, with 95% confidence intervals of 0.134 $\pm$ 0.0045 and 0.132 $\pm$ 0.0047 mg g^{-1}. These values are significantly larger than those obtained from values derived from fitted parameters (Table 2-2).

Discrepancies between batch and column-measured adsorption parameters have been noted by others (Nkedi-Kizza et al., 1982). The value of RF calculated using the batch-derived K_D value (including a coarse fragment content of 3.9% in the column) is 1.26, which is slightly higher than that obtained from curve fitting (1.17). This discrepancy is likely due to differences in the condition of the soil when the experiments were performed. The batch isotherms were conducted on air-dried or oven-dried soil while the columns were never air-dried.

When all unsaturated BTC's except the 0.1 kPa run were fit to the MIM model either extremely high w values (>35) or β values of 1 were obtained. From inspection, it is clear that Eqs. 2-20 and 2-21 are indistinguishable from Eq. 2-12 when β=1, and use of the MIM model is not justified. The effect of high w values is less clear but implies extremely rapid transfer between mobile and immobile regions which effectively eliminates the need to make a distinction between them. This will be discussed in greater detail in the next section.

Saturated Breakthrough Curves

The 0.1 kPa run (Fig. 2-1c) will be included in this part of the discussion because it more closely resembles the saturated BTC's than the other unsaturated BTC's. When the CD model was applied to the saturated BTC's generally poor fits resulted. This was due to the very rapid rise in C/C_o and obvious leftward shifting. Use of the MIM model

requires specification of 4 dimensionless variables; P, RF, β, and w. Although it is possible to allow all variables to vary simultaneously, the resultant parameter estimation is relatively imprecise. One value, RF, should be consistent with those derived from the unsaturated (CD model) BTC's. This value was accordingly taken from the unsaturated curves and fixed during parameter estimation for the saturated curves.

In every case, very close agreement between measured and calculated BTC's was obtained. In general, the parameter values in Table 2-2 indicate the following trends; very small P values corresponding to extremely large D values; β values on the order of 0.23 to 0.45; and w values ranging from 0.33 to 3.84.

Table 2-3. Mobile-immobile water model parameter values.

Col. No.	P	RF	β	w	D	ESR	Φ
					cm^2/hr	cm	
1 (fast)	0.29 (0.01)*	1.12	0.76 (0.03)	1.02 (0.39)	2515	0.18	0.81
1 (slow)	0.86 (0.05)	1.12	0.43 (0.04)	2.46 (0.45)	150	0.61	0.47
1 (1kPa)	1.11 (0.03)	1.12	0.84 (0.04)	0.08 (0.03)	437	0.51	0.89
2	0.43 (0.03)	1.13	0.34 (0.03)	3.84 (0.48)	1643	0.18	0.37
3	0.55 (0.03)	1.17	0.34 (0.03)	2.99 (0.48)	2758	0.19	0.38
4	0.76 (0.30)	1.15	0.23 (0.05)	0.16 (0.03)	3497	0.86	0.26
5	0.14 (0.02)	1.17	0.45 (0.11)	3.89 (2.53)	7525	0.15	0.51

* Numbers in parenthesis are the 95% confidence intervals associated with the estimated value.

The very low P values are indicative of an extremely broad range in pore-water velocities in the mobile water region. This indicates that the compartmentalization of soil-water into only two phases assumed in the MIM model was insufficient to account for the range of pore-water velocities encountered. It is possible that the logic of the MIM model be extended to consider gradations of soil-water mobility (e.g., "very rapidly mobile water", "somewhat rapidly mobile water", etc.). Skopp et al. (1981) have applied this approach but to only two soil-water phases. Recent work applying the transfer function model developed for soil applications by Jury (1982) to the analysis of BTC's similar to the saturated BTC's presented here (White et al., 1986) have described the distribution of pore-water velocity as a continuous, albeit skewed, function. Viewed in this perspective the MIM model may be considered to represent an extreme, bimodal pore-water velocity distribution.

Calculation of D from fitted P values is somewhat questionable when P values are so low. There are two sets of boundary conditions that approximate the experimental conditions and the solutions to those boundary conditions diverge when P is less than 4 or 5 (see van Genuchten and Parker, 1984; Parlange et al., 1985).

The parameter β means little on its own, but can be related to the mobile water fraction, Φ (recall that $\Phi=\Theta_m/\Theta$) with the expression $\Phi=(RF\beta)-f(RF1)$. Note that, if RF=1,

$\Phi=\beta$. As a first approximation, β can be considered to be a measure of Φ in these experiments because RF is close to 1. A more refined estimate of Φ is obtained if some assumptions concerning f are made. Recall that f was defined as the fraction of sorption sites in the mobile region. If the distribution of sorption sites is independent of location in soil-water regions, then $f=\Phi$ when the soil is saturated and $\Phi=\beta$. However, it seems reasonable to expect that proportionately more sorption sites will be found in immobile than mobile regions because the pores in immobile regions should be smaller and therefore have more exposed surface area. This reasoning has been used to justify the assumption that f=0 (Nkedi-Kizza et al., 1982) which leads to $\Phi=RF\beta$. Thus, in soils with positive adsorption, Φ values of greater than β are expected. The Φ values in Table 2-3 were calculated assuming that $f=\Phi/2$, which is an intermediate estimate.

The results in Table 2-3 indicate that Φ values of 0.25 to 0.50 are generally consistent with the parameters fitted with the MIM model. These values are surprisingly high in light of the large changes in K that resulted from relatively small changes in Θ. An independent estimate of Φ can be obtained by assuming that water held at field capacity is immobile (Addiscott et al., 1977). In this case, such an approach yields estimates of Φ of approximately 0.156, which is distinctly lower than those obtained from curve-fitting. When this value was fixed along with RF the resultant P values were increased, w values were decreased and the

goodness-of-fit was substantially reduced. These fitted curves were too angular, displaying a more rapid rise in effluent concentration with greater tailing than the measured BTC's. The difficulty of obtaining independent estimates of Φ has been noted by others (Addiscott et al., 1978).

The parameter w is somewhat more difficult to interpret as it is not directly related to any specific soil characteristic or property. However, work by Rao et al. (1980a) has shown that w can be used to successfully calculate inter-aggregate concentrations during diffusion into spherical aggregates of known volume. In subsequent work (Rao et al., 1982) it was demonstrated that media composed of different sizes and shapes of aggregates could be approximated by a single "equivalent" spherical aggregate size on a volume-weighted basis. This work has recently been extended to miscible displacement studies by van Genuchten (1985).

Using analytical solutions for flow through media composed of immobile regions of known geometry van Genuchten (1985) was able to express w in terms of an average sphere or other aggregate shape. This technique was applied to the saturated BTC's to determine size of effective spherical radius (ESR) consistent with the fitted parameter values. The parameters shown in Table 2-3 indicate that the soil may be considered to be composed of spherical aggregates of of 0.15 to 0.6 cm radius.

Another way of considering the effect of aggregate size on the effective pore geometry was presented by Rao et al. (1980b). They showed that, when the aggregate size is small enough relative to the pore-water velocity, a condition of near-equilibrium will be established and the CD model should be appropriate. For spherical aggregates, the condition of near-equilibrium is valid when

$$D_e L(1-\Phi)/(a^2 v_o^2 0.3) \geq 1 \qquad (2\text{-}22)$$

where D_e is the diffusion coefficient and L is the column length (Rao et al., 1980b). Taking ESR as 0.5 leads to a critical v_o of 1.6 cm/hr, which is generally less than the v_o values of the unsaturated runs ($v_o \approx 2q$ in these columns). Thus spherical regions of immobile water could exist in the columns but their effect on solute transport would be "masked" as high dispersion.

Taken as a whole, some inferences concerning the nature of the effective pore geometry of the soil can be made. The high K_{sat} values measured in conjunction with highly skewed BTC's indicate that water was conducted relatively rapidly through some portion of the soil when saturated. The large reduction in K and BTC skewedness that resulted from application of 0.1 to 0.5 kPa of tension suggests that soil water was rapidly conducted via macropores (Luxmoore, 1981; Germann and Bevin, 1981). However, the extremely low P values and Φ values of 0.25 to 0.50 under saturated conditions suggest that there were several such regions of varying conductivities. The model parameter values obtained

are consistent with fairly large regions of immobile water. If immobile regions are assumed, for example, the immobile regions would have radii of 0.15 to 0.6 cm.

Although immobile regions were described in terms of spherical aggregates, the MIM model specifies no pore geometry and numerous other possibilities exist. Rhodamine B dye was used to better determine the actual effective pore geometry.

Dye Experiment

Dyes have frequently been used to visually investigate the nature of flow paths through the soil (Bouma and Dekker, 1978; Omoti and Wild, 1979; McVoy, 1985). The approach provides the opportunity to observe the conducting pathways and thereby relate water and solute flow to observable structural features or biochannels. The basic assumption made in interpreting dye patterns is that the more solution that passes a given point, the more darkly stained that point will be. Thus, stained regions are interpreted as being regions of relatively fast flow, unstained regions to be of relatively slow flow.

It is important that this fairly simple-minded approach not be extrapolated far in terms of correlation of dye patterns with BTC's. In the first place, Rhodamine B dye is sorped to the soil much more strongly than tritium (McVoy, 1985) so that dispersion is apparently reduced. Secondly, the dye is not instantaneously and reversibly desorped as tritium is assumed to be. And thirdly, visual evaluation of

color is qualitative, so that quantification of the amount of dye at a location is not possible.

Given these difficulties, four observations of note can be made from the dye patterns illustrated in Figs. 2-6 through 2-9. First, no significant staining of the column edges was observed in Columns 1, 2, and 3 and the staining on the edge of Column 4 was not as intense as in the internal portions of the column. This is a critical question that must be considered when undisturbed columns are used. From these observations we do not believe that observed BTC's were strongly affected by the presence of the column boundary.

Second, while specific stained regions that must have been responsible for the very early appearance of tracer in the effluent were easily identified, with one exception, they were not obviously associated with discrete biochannels or structural features. Even with the segmented column at hand, it was very difficult to determine exactly which pores were conducting, as, in every case many visible pores were stained. In addition, it was difficult to trace individual pore sequences up the column because they meandered considerably across the column. Omoti and Wild (1979) and McVoy (1985) have made a similar observations.

Third, where structural units were relatively strong as in Column 1, there was preferential flow around them. The structural units isolated in Column 1 ranged in radius from about 0.3 to 1.2 cm, which is in rough agreement with that

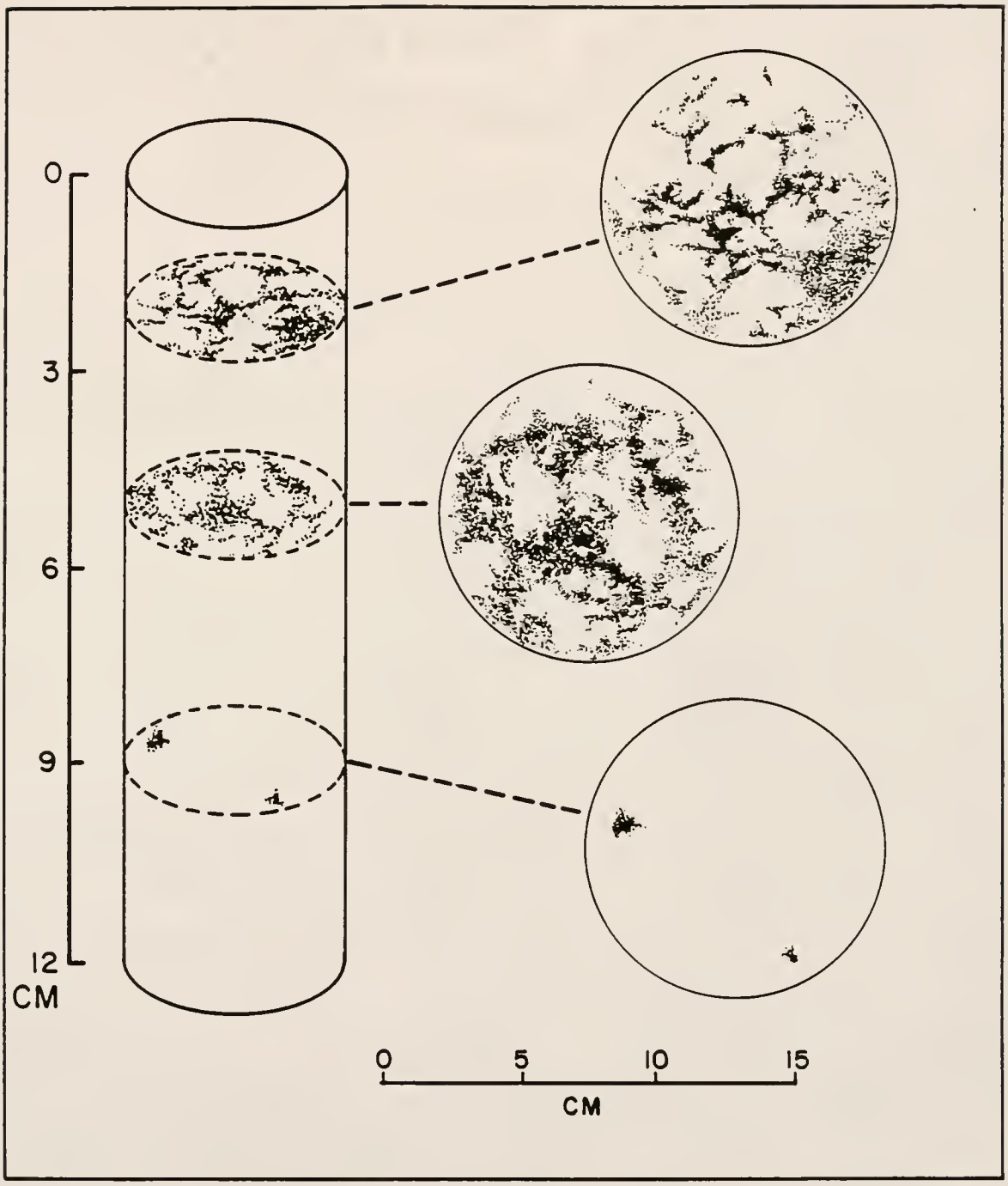

Figure 2-6. Rhodamine B dye staining pattern in Column 1 resulting from displacement under a soil-water tension of 1 kPa.

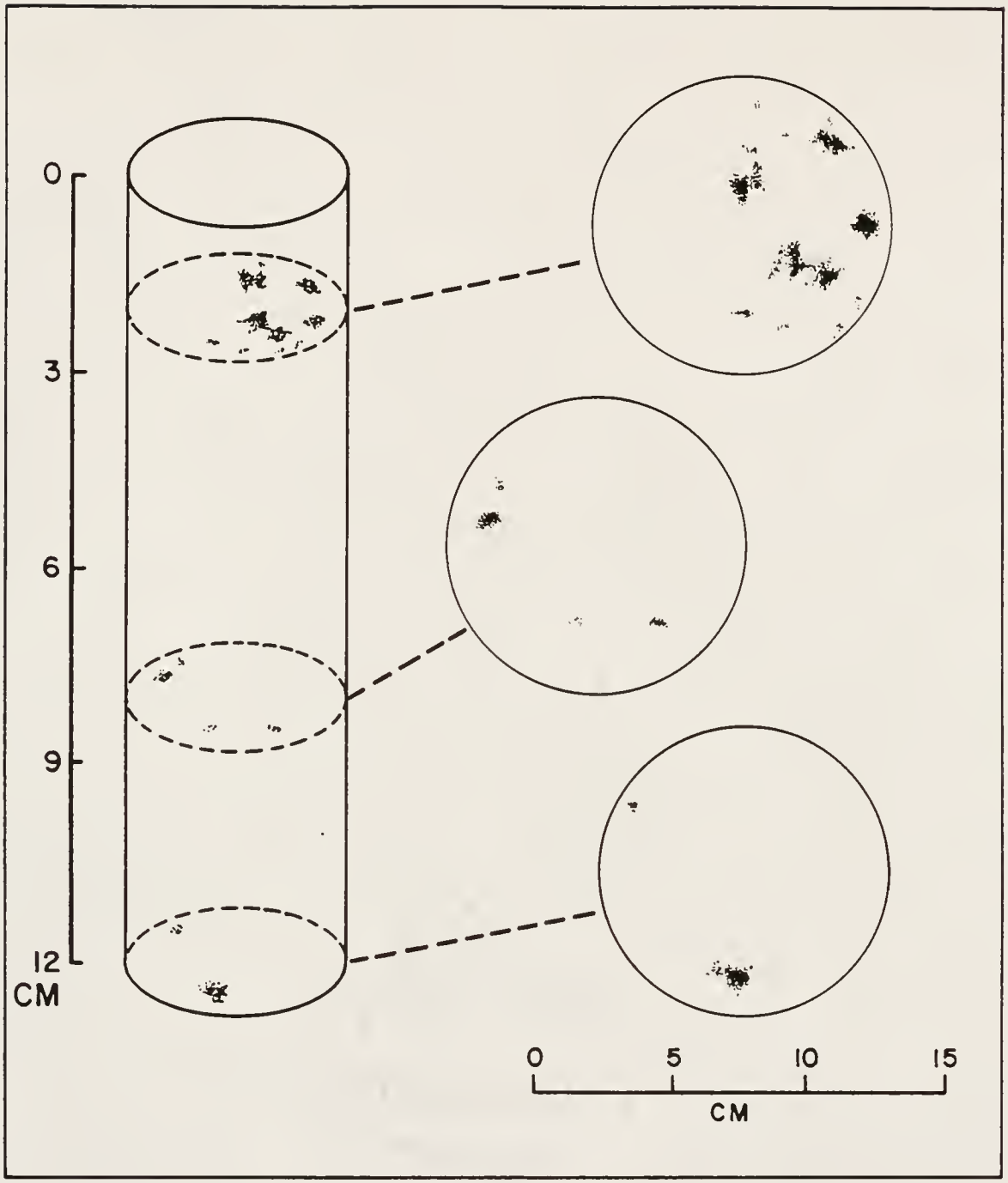

Figure 2-7. Rhodamine B dye staining pattern in Column 2 resulting from displacement under saturated conditions.

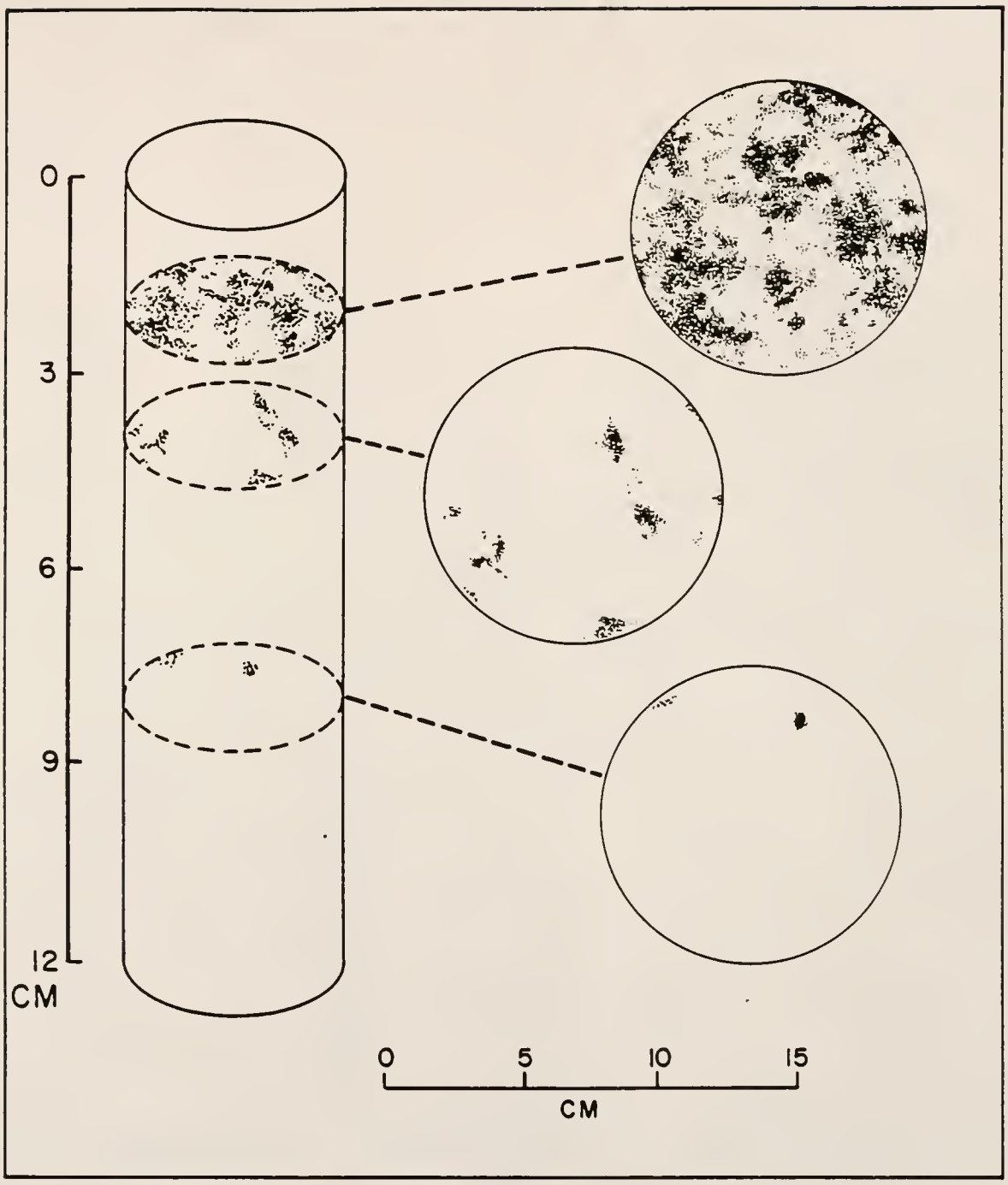

Figure 2-8. Rhodamine B dye staining pattern in Column 3 resulting from displacement under saturated conditions.

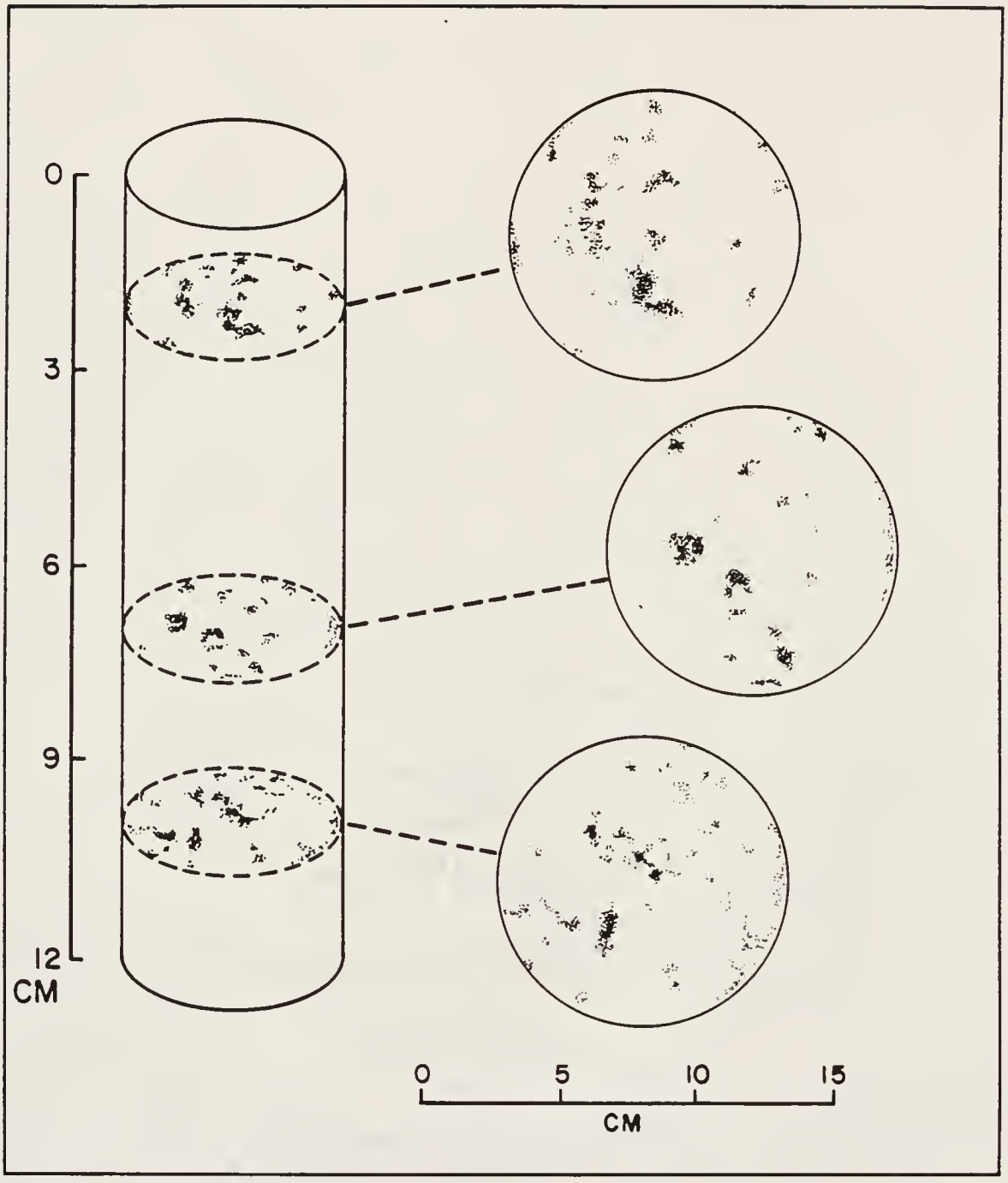

Figure 2-9. Rhodamine B dye staining pattern in Column 4 resulting from displacement under a soil-water tension of 1 kPa.

calculated from the curve-fit parameters. The fact that these units were identified during unsaturated flow which was well described by the CD model indicates that movement into and out of those units was sufficiently rapid that bypassing was not indicated in the BTC. This observation probably accounts for the generally greater dispersion observed in undisturbed columns and field studies. That is, bypassing is "masked" in the dispersion term.

Fourth, the nature of the stained regions does not appear much different in the saturated and unsaturated columns. This is evidence that, rather than drain a few, discrete large pores, the application of tension drains regions of the soil that serve to "connect" pore-sequences.

The main difference between saturated and unsaturated dye patterns is that the "solute front" is more compressed in the unsaturated columns. Note that the number of pore volumes of dye solution applied to all columns was approximately the same (Table 2-1), but the extent of staining in the unsaturated runs was more strongly weighted toward the inlet end of the column.

These observations compliment the results of BTC analysis and hydraulic property measurement in the previous section. It appears that the highly skewed BTC's and very high K_{sat} measured under saturated conditions were due to very rapid transport in a very restricted region of the columns. These regions are better characterized as conducting pore sequences than discrete macropores and their

identification in the field would be very difficult. There appears to be a number of such pore sequences that range widely in conductivity. Application of tension "disconnects" the largest effective pore sequences and therefore results in reduced skewing and K. Immobile regions were generally characterized as regions between conducting pore sequences as opposed to easily identifiable, physically controlled regions. When displacement occurred under tension, flow in the conducting regions was slow enough, and those regions were close enough, that observed heterogeneous flow was described as dispersion with the CD model.

Field Application

One of the stated objectives of this study was to use information from column experiments as a basis for selecting a model to describe movement of nutrients and water under field conditions. The basic distinction between the two models considered is whether or not all soil-water effectively participates in convective transport (i.e., whether or not v_o applies). It is clear from the dye patterns in Figs. 2-6 through 2-9 that there was bypassing in the sense of heterogeneous flow under both saturated and unsaturated conditions. In terms of model selection, however, bypassing was significant only when the soil-water content was at or very near saturation. Hence, "significant" bypassing is expected in the field only when the soil is near saturation.

The necessary precondition for saturation of the soil surface under field conditions is that the water input rate

(rainfall intensity) exceed the infiltrability of the soil (Hillel, 1971). If no surface disturbance occurs (none was observed) the minimum infiltrability of a uniform soil profile is K_{sat}. Since no differentiation of horizons in terms of hydraulic properties was observed, the rainfall intensity must at least exceed K_{sat} if saturation and hence "significant" bypassing are to occur.

The K_{sat} values measured in undisturbed columns were between 20 and 40 cm hr^{-1}. Given the well known high spatial variability of K_{sat} (Warrick and Nielsen, 1980), these values probably should not be used in this context. We obtained estimates of K_{sat} from 24 double ring infiltration measurements. The results are shown in Fig. 2-10. The values obtained are considerably lower than those measured in the columns. Aside from spatial variability, two explanations for this difference are the fact that the columns were saturated from below under tension and were therefore closer to true saturation and the fact that macropore continuity is enhanced in shortened columns (Edwards et al., 1979)

When the frequency distributions of K_{sat} and rainfall intensity are compared (Fig. 2-10), it is evident that rainfall intensity sufficient to cause ponding is rare. Based on this information it appears that saturated flow and the attendant bypassing are not expected to occur at the site. This is consistent with the observation at the site that ponding did not occur.

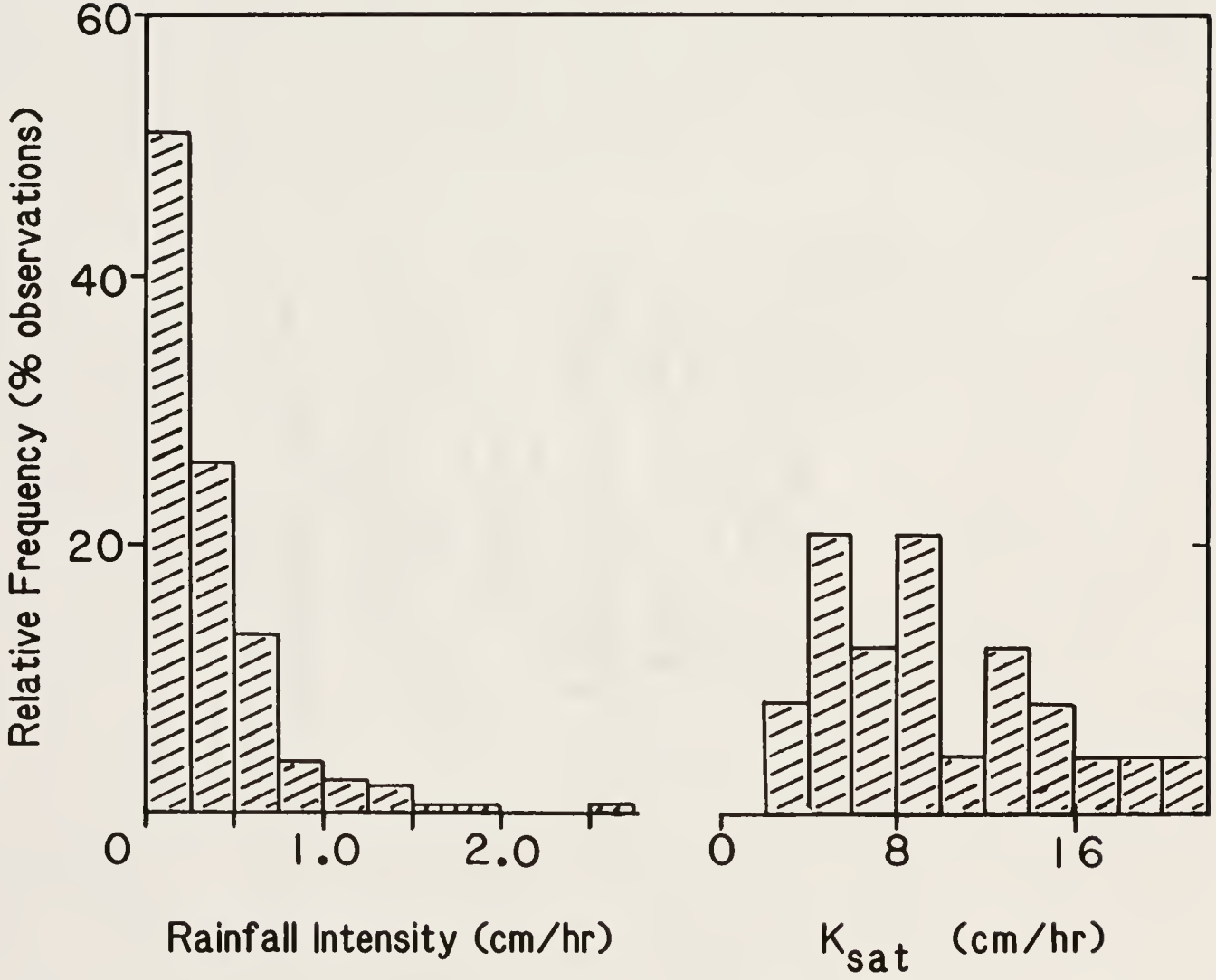

Figure 2-10. Relative frequency of rainfall intensity and saturated hydraulic conductivity estimated with a double ring infiltrometer.

Application of BTC's measured in columns to field conditions involves a considerable extrapolation in scale. This requires that the representative elementary volume (Bear, 1972) for bypassing be considerably less that the volume of the column. Several studies have shown that measured bypassing at a field scale was expressed in undisturbed soil columns (Bouma and Wosten, 1979; Omoti and Wild, 1979; White 1985). This, however, need not be the case.

If significant bypassing at a scale larger than column dimension is to occur, there must be some means by which soil water movement is concentrated. This may be the result of soil properties or the distribution of incoming water. Large soil structural units or biochannels have been shown to be responsible for bypassing (Bouma and Dekker, 1978; Bouma et al., 1982). These effects are enhanced by a very slow matrix K_{sat}. Other soil characteristics that could serve to concentrate flow are coarse fragments, steep slopes, and strongly contrasting horizons (Bevin and Germann, 1982).

The soils in this study exhibited none of the above characteristics. Soil structural units were generally less than 2 cm in diameter and poorly expressed. From the column studies it is clear that the matrix conductivity is relatively high (>1 cm hr^{-1}). Other characteristics such as steep slopes, contrasting horizons and coarse fragments were not evident. Soil animals that could potentially make large channels (e.g., leaf cutter ants and armadillos) were

carefully excluded from the site.

The input of water may have been concentrated in two ways. First, the reported intensities are averages over the entire event so that much higher intensities would prevail for short time periods. Second, vegetation causes a spatial redistribution of incoming rain such that small areas of much higher intensity than the average are expected. On the other hand, it should be considered that K_{sat} is the minimum infiltrability and that lateral movement away from local high intensity spots is likely.

Rapid changes in water table depth and/or stream discharge have been cited as evidence for bypassing (Thomas and Phillips, 1979; Beven and Germann, 1982). Thomas and Phillips (1979) noted that water in macropores can flow into or below the rooting zone in a matter of minutes and described flow from a spring 30 minutes after cessation of a large (4.57 cm) rainfall.

From 1 September to 24 July, 1982-1983, the water table depth was monitored about 5 times each week. At the same time, a daily record of precipitation was maintained. Measured water table depths ranged from 80 to 200 cm. The length of time between rainfall events and rise in water table depth could be estimated only to within 24 hours because measurements of both rainfall and water table depth were made at approximately the same time (7:00 AM). Therefore, if a rise in water table depth and rainfall were recorded on the same morning, the water table response could

have occurred between 0 and 24 hours after the rainfall event. On the other hand, if no change in water table depth was recorded the following day, either the incoming water was absorbed in the soil above the water table or the response took longer than 24 hours.

During the 11 month measurement period there were 27 rainfall events of less than one cm had no measurable effect on water table depth. Among the rainfall events greater than 1 cm, there were 27 for which the water table depth was recorded both the day of the event and the day following and that were not immediately preceded by large (>1.0 cm) events. Of these there were 23 for which no response was recorded the following day. The remaining 4 events occurred when the soil was relatively moist (there had been between 3.2 and 6.6 cm of rain during the preceding 5 days) and the water table was between 128 and 143 cm deep. If conditions of field capacity and moderate (0.5 cm hr^{-1}) rainfall intensity are assumed, infiltration as calculated by the Green-Ampt method (see Hillel, 1971) to a depth of 100 cm or greater within 6 hrs is expected. Given this estimation, rapid arrival of water at the water table is expected. Thus, no evidence in support of macropore flow could be found.

From this information it appears that macropore flow was not common and that it likely did not occur during the period of measurement. This is consistent with other findings in the field and laboratory. From this we conclude

that the CD model, or other simplified models based on the concept that all soil-water participates in convective transport of solutes, should be appropriate for describing solute flow in this soil.

It is important to note that, at this time, we do not have criteria for simple determination of bypassing in the field. Recent work by Russel and Ewel (1985) performed near our experimental site reported considerable amounts of flow through selected channels. Many of the soil characteristics described above as being related to bypassing on a large scale were present at that site. These included, steep slopes, the presence of large coarse fragments, a mixed canopy, and the presence of native soil fauna. It may also be noted that their observations of bypassing were restrict to two large events and relatively small portion of the total surface area. While the effects may be significant on a hydrologic scale, they may not be in terms of calculating nutrient losses by leaching.

CONCLUSIONS

Solute breakthrough curves resulting from miscible displacement of $^{3}H_2O$ in undisturbed soil columns under a range of soil-water tensions were evaluated in terms of the mobile-immobile water model and the convective-dispersive model. Model parameters derived from curve fitting indicated that the convective-dispersive model accurately described breakthrough curves performed under tensions greater than

0.1 kPa while the mobile-immobile model better described breakthrough curves performed under soil-water tensions less than or equal to 0.1 kPa. Thus, in terms of model selection, bypassing was significant only when soil-water contents were at or very near saturation.

Dye patterns obtained under saturated conditions showed that soil-water flow (and thus convective transport) was confined to small regions within the columns. However, no easily identifiable, discrete channels were observed in these regions. It appears that flow was conducted via a series of relatively large pores, or continuous pore-sequences. The net effect of the pore sequences on soil hydraulic conductivity was identical to discrete channels, but the identification of the channels responsible is virtually impossible.

Application of tension appears to have disconnected the most rapidly conducting pore-sequences, thus reducing the skewedness of breakthrough curves. Under unsaturated conditions the conducting pore-sequences were slow enough, and well enough interconnected with the rest of the soil, that the convective-dispersive model was applicable. Even so, dye patterns showed that flow was very heterogeneous, as was also evidenced by high dispersion coefficients.

Comparison of the frequency distributions of field-measured K_{sat} values and measured rainfall intensities indicated that saturated conditions, and hence significant bypassing, are not expected to occur in this soil.

Observation of water table response to rainfall events supports this. Based on these experiments, we conclude that field-scale models based on the convective-dispersive model for solute movement should be applicable this soil.

CHAPTER III
LEACHING LOSSES FROM TWO CONTRASTING CROPPING SYSTEMS

Introduction

There is a large and increasing demand for increased food production from humid tropical regions. The climate of these regions is characterized by very high annual rainfall that is considerably in excess of potential evapotranspiration. Under these conditions there is a large potential for loss of nutrients by leaching. This has been cited as a major limitation to the transfer of fertilizer technologies developed in temperate zones to humid tropical regions (Engelstad and Russel, 1975). It is especially important, therefore, that loss of nutrients by leaching be considered in the development of cropping systems in the region. One approach that has been proposed is to manipulate cropping systems so that land is continuously planted to a variety of crops (Cox and Atkins, 1979). Reduction of leaching loss is among the many benefits ascribed to such systems.

Measurements of nutrient loss from agricultural fields in the tropics are rare (Greenland, 1977; Keeney, 1982; Omoti et al., 1983). Those results that have been published indicate a very wide range in leaching losses (e.g., Sanchez, 1976). The lack of leaching studies is due, at least in part, to the numerous difficulties associated with

such measurements. The fundamental difficulty is that there is no known means of directly measuring solute leaching losses. Indirect methods must be employed.

One method that is commonly employed is to use a mass balance based on the equation:

$$\Delta F = F_a - F_u - F_l, \qquad (3\text{-}1)$$

where F (kg ha^{-1}) refers to the change in storage of any given nutrient and the subscripts "a", "u", and "l", refer to the amounts of nutrient applied, taken up by the crop, and lost by leaching, respectively. From an agronomic point of view, this is reasonable since the amount taken up by the crop, which is really the object of nutrient application, is evaluated. The chief limitation to this approach is that Eq. 3-1 is incomplete. In addition to plant uptake and leaching, nutrient dynamics are governed by other processes, e.g., immobilization and denitrification of N and fixation of K. Another problem is that the amount of nutrient stored in the root mass is usually poorly known.

Another method used to calculate nutrient leaching is to calculate the convective solute flux from the the rooting zone with the equation:

$$J = q\ C \qquad (3\text{-}2)$$

where J is the solute flux (mg cm^{-2} day^{-1}), q is the soil-water flux (cm day^{-1}), and C is the soil solution concentration (mg cm^{-3}). This provides a direct estimation of leaching loss that is independent of other processes that effect the fate of an applied nutrient. The method requires

knowledge of q and C. The value of q can be calculated using Darcy's law, but the spatial variability of the soil hydraulic conductivity is so large that this approach is generally impractical for field-level research (Warrick and Nielsen, 1980). An alternative is to calculate q from water mass balance. This method provides an areal estimate of the net water movement. Estimation of C can be based on measurements of the soil solution at specific locations in the field, which can be made with quantifiable precision.

This approach can be extended to trace the movement of a solute through the crop rooting zone. This provides information concerning the length of time a solute (e.g., an applied nutrient) can be expected to reside in the crop rooting zone under known soil, plant and weather conditions.

Water Balance and Nutrient Leaching

If the system of interest is considered to be delineated by a unit surface area of soil extending to the depth of the crop rooting zone, then, assuming that the mass of water is conserved, $\Delta W = W_{in} - W_{out}$, where W is the mass of water and the subscripts "in" and "out" refer to water entering and leaving the system. This expression can be decomposed into a number of components such that:

$$\Delta S + \Delta RW = (P+I+UP+RON) - (E+T+\Delta PA+ROF+DP), \qquad (3\text{-}3)$$

where S = soil profile water content

RW = water held in the roots,

P = precipitation,

I = irrigation,

RON = runon of water from adjacent soil,

UP = upward percolation,

E = evaporation,

T = transpiration,

PA = water stored in the above-ground biomass,

ROF = runoff of water to adjacent soil, and

DP = deep percolation,

with all components expressed in units of cm (the density of water is assumed to be 1 g cm^{-3}). This general equation can usually be simplified considerably when adapted for a specific location and set of objectives. Based on observations in the field, I, RON, and ROF equal 0 in this study. In addition, the assumption was made that, relative to the magnitudes of the other components, ΔRW can be ignored and ΔPA can be lumped with transpiration. For practical reasons, E and T were lumped into the single term, evapotranspiration (ET). Thus,

$$\Delta S = (P+UP) - (ET+DP). \quad (3\text{-}4)$$

If the net deep percolation (NDP) is defined as DP-UP and substituted into Eq. 3-4, the result is as follows:

$$NDP = P - ET - \Delta S. \quad (3\text{-}5)$$

In general, S and P can be measured directly, ET can be estimated from measured parameters, and NDP can then be calculated as the difference. It is apparent that the accuracy with which NDP can be determined in this way is dependent on the accuracy with which the other three parameters are determined.

This fairly straightforward approach is complicated by the fact that ET is a function of S (or soil-water potential) when conditions of soil-water stress are encountered, which requires either that S be determined frequently, or that S be estimated between measurements. In addition, it provides no information about water movement between S measurements or within the system.

Models based on the use of Eqs. 3-2 and 3-5 that incorporate soil and crop parameters have been developed to overcome these limitations (Rao et al., 1981; Rose et al., 1982a). They apply this approach incrementally to layers within the system and can thereby provide more information about water and solute movement over depth within the system and out of the system over time.

Model Development-Concepts

The model used in this study fits the general classification of capacity-parameter based models (Addiscott and Wagenet, 1985). Water movement is calculated from differences in amounts of water stored. Specific processes governing the rates of movement are explicitly ignored. The advantages of this approach over other, rate models, are that the required parameters are generally easier to measure and exhibit considerably less spatial variability (Warrick and Nielsen, 1980). The disadvantage of capacity models is that, because they are empirical representations of processes, they lack the flexibility of more process oriented models. For this reason it is important to carefully

consider the relationship between the processes of interest and the empirical representation of them.

There are two basic outputs desired from the model: (1) NDP, which is to be used to calculate movement of nutrients beyond the rooting zone using Eq. 3-2 with q = NDP, and (2) the time of solute residence in the rooting zone.

The following two assumptions are considered fundamental to the approach: (1) the position of a solute front of a nonadsorbed, conserved solute is dependent only on convective transport (i.e., dispersion and diffusion are not considered), and (2) drainage of soil water proceeds to a consistent soil-water content called the field capacity (Θ_{fc}).

Examination of solutions to the convective-dispersive equation indicate that, except where $v_o L/D$ (discussed in the previous chapter) is very low (i.e., when dispersion is very high), dispersion has relatively little effect on the position of a solute front. That is to say that solutes move in roughly symmetric pulses through the soil. Even under field conditions, where D is expected to be quite high, the effect of dispersion on the position of a solute front is small compared with other errors and the accuracy that is usually considered acceptable in field studies (Rose et al., 1982b).

From the first assumption, the traditional convective-dispersion equation is simplified to

$$\Theta \partial c/\partial t = -q \partial c/\partial z, \quad (3\text{-}6)$$

where Θ is the soil-water content ($cm^3\ cm^{-3}$). If one is interested only in tracking the depth of the solute front (DSF), the equation becomes;

$$[\partial DSF/\partial t] = (q/\Theta) = v_o, \quad (3\text{-}7)$$

where DSF is expressed in cm, and v_o is the average pore water velocity ($cm\ day^{-1}$). The importance of v_o as discussed in the previous chapter is apparent. Studies using packed soil columns have shown that the above principles are applicable to a wide range of textures and initial conditions (e.g., Dahiya et al., 1984). In general, it is expected that the approach will be valid for most field-scale applications if v_o is an appropriate descriptor of soil water movement. It is clearly inappropriate when water flows preferentially through large macropores or around large soil peds or aggregates.

Several studies have demonstrated the validity of the approach under a wide range of field conditions (Rao et al., 1976; Cameron and Wild, 1982; Barry et al., 1985). Such success, however, is by no means universal. Smith et al. (1984), working with a variety of soils over a three year period, found that agreement between measured solute front depths and those calculated with Eq. 3-7 ranged from excellent to poor, varying both with soil and year. Still other studies have shown the approach to be completely inappropriate (Addiscott et al., 1978; Bouma and Dekker, 1978; Thomas and Phillips, 1979; White, 1985). In these studies

preferential flow through macropores causing bypassing was cited as the reason for failure of agreement.

This work demonstrates that the applicability of the model to the specific conditions of interest should be tested. In the previous chapter it was demonstrated that, at the scale of 12.5 cm diameter undisturbed soil columns, such bypassing did not occur under flow regimes encountered in the field. Further evidence was cited that such behavior did not occur at the field level.

The second assumption (concerning Θ_{fc}) has seen a long history of controversy and it is clear that its application should depend on the objectives of the study and specifically measured values. It is based on the general observation that, upon cessation of infiltration, soils drain with decreasing rapidity over time. For uniform, well drained soils, drainage is commonly described with the following expression: $S = at^{-b}$, where a and b are arbitrary constants (Hillel, 1980). Thus, drainage never actually ceases, but becomes increasingly slow in finite time. The choice of Θ_{fc} and the length of time required to reach that value are arbitrary and depend on the soil in question and the objectives of the study. In addition, it is important to recognize that the relationship between soil water tension and soil-water content at field capacity depends on the soil (Ratliff et al., 1983).

When the second assumption is made, the eventual depth of leaching from a given infiltration event (I), if ET during redistribution is negligable, is

$$DSF = I/\Theta_{fc}, \quad (3\text{-}8)$$

where I is the amount of water entering the soil during an infiltration event (Rao et al., 1976). The significance of the assumption of a field capacity is that it allows the use of the amount of the event, which is relatively easy to measure and use in computations, as opposed to using rates and time intervals. Equation 3-8 has been modified ro account for the effects of evapotranspiration and movement of the solute front within the soil profile (Rao, et al., 1976; Davidson et al., 1978; Rose et al, 1982b).

Water Table Effects

Application of the modeling approach described above has been restricted to conditions in which a water table was not present. The presence of a fluctuating water table in close proximity to the rooting zone renders the second assumption invalid because the soil-water does not drain to field capacity as it is generally defined but to some greater value that depends on the location of the water table. In the extreme, at the water table interface, that value is the saturated water content of the soil (Θ_s). At increasing distances above the water table that value decreases, until at some point, it equals the "normal" field capacity.

The soil profile can therefore be divided into two regions; that above the influence of the water table, and that within the influence of the water table. The proportion of the soil profile in either region is variable, depending on the depth of the water table and the height of water table influence (HWTI). In the region above the HWTI, drainage is assumed to proceed as if no water table were present. Drainage in the region below the HWTI is assumed to proceed to a different, greater value. This value is considered to be a "temporary" field capacity, Θ_{fc}*, that is dependent on the position of the water table.

The relationship between field capacity, the HWTI, and the water table depth are illustrated in Fig. 3-1. Note that the soil-water content at the HWTI is equal to Θ_{fc} and that the water table represents effective saturation. Under the quasi-equilibrium conditions to which the soil is assumed to drain, the soil-water tension between the HWTI and the water table (measured in cm H_2O) is numerically equal to the height above the water table (expressed in cm). This is illustrated as a linear function in Fig. 3-1, but may be quite different, depending on the soil moisture characteristic of the soil. This relationship should be independent of the direction of water table movement if hysteresis effects are ignored.

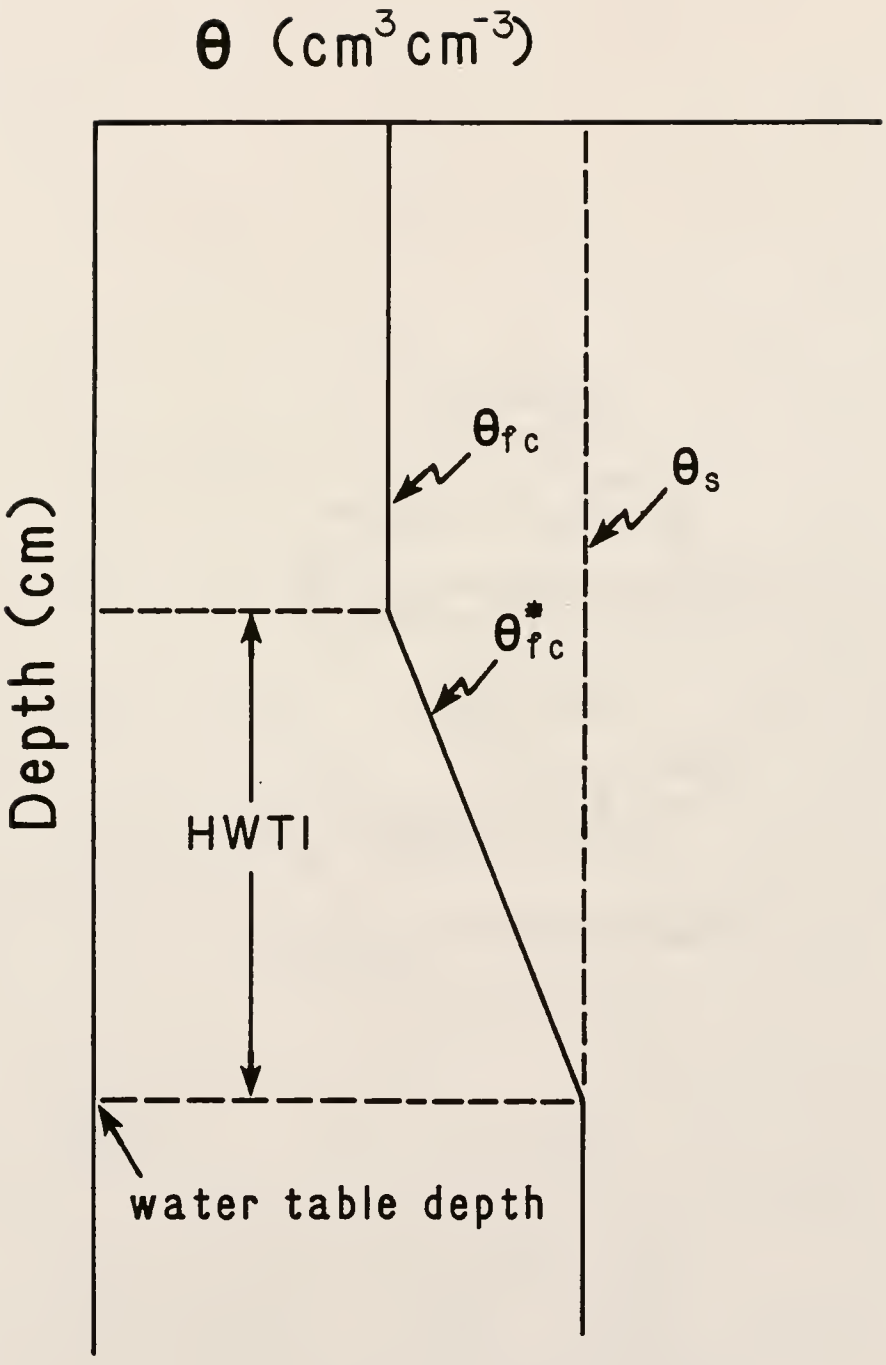

Figure 3-1. Schematic representation of the relationship between water table depth, the height of water table influence (HWTI), Θ_{fc*}, and Θ_{fc}.

Materials and Methods

Cropping Systems and Soils

The two cropping systems chosen for comparison were: (1) a mixed cropping system composed of laurel (*Cordia alliodora*), cacao (*Theobroma cacao*) and platano (*Musa paradisiaca*), and (2) a monocropping system composed of maize (*Zea mays* L.). These two cropping systems will be referred to as the MP, for mixed perennial, and the MA, for monocropped annual, cropping systems.

The sites of the two cropping systems were separated by approximately 100 m and were located in the "la Montana" section of the experimental plots at CATIE (Centro Agricola de Investigaciones y Ensenanzas) near Turrialba, Costa Rica. Both cropping systems were planted on Instituto clay loam, which is classified as a Typic Dystropept, fine, mixed, isohyperthermic (Aguirre, 1971).

The management level of both systems was designed to promote high yields and profitability. The MA plot is located in a larger study area used by Dr. Carlos Burgos to study the effects of tillage and residue management on maize yields. It was initiated in November of 1976. A 120-day variety was planted at a density of 40,000 plants ha^{-1}. Two crops were planted each year, one in late May, and the other in early November. Approximately 240, 55, and 40 kg ha^{-1} of N, P, and K, respectively, were applied each year. Applications were made on the planting date and approximately 30

days after planting, resulting in 4 applications each year. The plot dimensions were 32 by 20 m.

The MP plot was part of a larger study of intercropping with perennial crops directed by Dr. Gustavo Enriquez. It was initiated in 1977. The planting densities were 1,111; 432; and 123 plants ha^{-1} for cacao, laurel, and platano, respectively. The annual fertilizer regime was 140 kg ha^{-1} N, 30 kg ha^{-1} P, and 20 kg ha^{-1} K in four applications. The dimensions of the MP plot were 18 by 18 m.

Model Developement-Construction

The model used in this study was based on the model, NITROSIM, developed by Rao et al. (1981). Water movement was divided into three phases; infiltration, redistribution, and static. Calculation of soil-water content (Θ^i) and flux (q^i) for depth increments (i=1,2,...n) of thickness of Δz cm within the soil profile was an iterative process carried out at discrete time increments (Δt).

Infiltration was assumed to proceed as a "square pulse" (i.e. Green-Ampt infiltration) within one time increment at an infiltration soil-water content (Θ_{inf}) where $\Theta_{fc} < \Theta_{inf} < \Theta_s$. Assumed ET during infiltration was 0. The depth of the wetting front (dwf) resulting from a rainfall event of I cm was calculated such that

$$I = \Sigma (\Theta_{inf}{}^{i} - \Theta^{i})\ dwf, \quad i=1,2,...,n. \qquad (3\text{-}9)$$

The change in DSF (ΔDSF) resulting an infiltration event, I, was calculated as

$$\Delta DSF = 0 \qquad I \leq \Delta W \tag{3-10}$$

$$\Delta DSF = (I - \Delta W)/\Theta_{inf} \qquad I > \Delta W \tag{3-11}$$

where

$$\Delta W = \Sigma(\Theta_{inf}{}^{i} - \Theta^{i})\Delta z, \quad i = 1,2,\ldots,m \tag{3-12}$$

and m is the depth increment in which DSF resided prior to the event.

Redistribution calculations were based on the following expression:

$$\Theta = \Theta_{fc} + (\Theta_{inf} - \Theta_{fc}) \exp(ct), \tag{3-13}$$

where TRD is the length of time required for the soil to drain to field capacity. In this way Θ decreases "exponentially" to a value within 1% of Θ_{fc} after TRD days of drainage.

In the algorythm used to update Θ, q, and DSF described below, $\Theta^{i'}$ is used to denote Θ^{i} at $t = t + \Delta t$. Calculations proceeded from the upper depth increment (i=1) down as follows:

$$q^{1} = 0 \tag{3-14}$$

$$\Theta^{1'} = \Theta_{fc} + (\Theta^{1} - \Theta_{fc}{}^{1}) \exp(c\Delta t) \tag{3-15}$$

$$q^{2} = (\Theta^{1'} - \Theta^{1}) \Delta z/\Delta t \tag{3-16}$$

and, for $i > 1$ and $\Theta^{i} \geq \Theta_{fc}$,

$$\Theta^{i'} = \Theta_{fc}{}^{i} - \Theta^{i} - \Theta_{fc}) \exp(c\Delta t), \tag{3-17}$$

$$q^{i+1} = (\Theta^{i'} - \Theta^{'}) \Delta z/\Delta t + q^{i}, \tag{3-18}$$

or, for $\Theta^{i} < \Theta_{fc}$,

$$\Theta^{i} = q^{i} \Delta z/\Delta t + \Theta^{i} \qquad \Theta^{i} < \Theta_{fc}. \tag{3-19}$$

For depth increments within the crop rooting zone ET is included so that

$$\Theta^{i'} = \Theta^{i'} - U^{i} \Delta t \qquad (3\text{-}20)$$

where U^{i} is the rate of ET from the i-th depth increment. Changes in DSF (ΔDSF) were calculated as

$$\Delta DSF = DSF + q^{i} (\Delta t/\Delta z \Theta^{i}) \qquad (3\text{-}21)$$

when DSF was in the i + 1 depth increment at time t.

Some modifications were required to incorporate water table effects. The water table depth was an input to the model taken from measured and interpolated values. The HWTI and Θ_{fc}^{*} (Fig. 1) were calculated on a daily basis from the water table depth. All water entering depth increments within the HWTI in excess of that required to account for measured changes in water table depth was considered to be NDP. Redistribution within the HWTI proceeded as described above with Θ_{fc} replaced by Θ_{fc}. Upward movement of water was not explicitly considered.

The static phase commenced after field capacity was achieved. During that phase changes in soil-water content occurred only as the result of ET. Note that redistribution could result from either infiltration events of a lowering of the water table.

The soil profile was divided into 22, 5 cm increments for numerical computations in the simulation model. Thus the total depth of interest of 110 cm. The time step used for calculation of water and solute movement was 0.1 day. Days were considered to begin at 7:00 AM, when measurements of water table depth, rainfall, and soil-water content were made. Rainfall events were assumed to take place at 4:00

PM, which is roughly the most common time for such events. All programming was done on a VAX-11 minicomputer in FORTRAN-77.

Determination of Inputs

Use of the model requires as input the rainfall, potential evapotranspiration, water table depth, initial soil water content, and the soil and plant parameters. Rainfall was measured daily with gauges located adjacent to each plot. The water table depth to 220 cm was measured about 5 times each week in perforated PVC tubes located in the center of each plot that served as piezometers. Model outputs were generated for two different time periods, the simulation period and the calibration/validation period, which are described subsequently. The initial soil-water content for the simulation periods was determined gravimetrically and for the calibration/validation period with a neutron probe.

Soil samples for soil-water content determination were taken at 10 cm intervals from 6 auger holes in the MP plot and 9 holes in the MA plot. Soil-water content was determined by weight loss after drying at 110^{o} C to a constant weight. This was converted to a volumetric basis by multiplication with the soil bulk density.

Two methods were used to calibrate the neutron probe. First, counts were made simultaneously with gravimetric sampling approximately 1 meter from the access tube. Second, a large tub was filled with soil taken from an

adjacent plot. The soil was then mixed and adjusted to three different soil-water contents, packed into the tub, and measured. Counts measured in the tub were adjusted for bulk density as suggested by Greacen et al. (1981). The resultant calibration curve, including field and tub-measured values are shown in Fig. 3-2. There were five access holes in each plot and counts were made at 15-cm intervals from depths of 20 to 110 cm.

Evaporation from a class A US Weather Bureau pan located approximately one km from the site was the basic input used for calculating the potential evapotranspiration (PET). The measured pan evaporation (E_{pan}) was converted to PET using the equation PET = k E_{pan} where k is the pan constant, taken from Doorenbos and Pruitt (1974) as 0.8.

Soil Parameter Estimation

Soil profiles were assumed to be uniform over the depths of interest with respect to the required soil hydraulic parameters because only small trends with depth were observed in the plots. There were some differences in soil properties between the two plots used in the study even though they were separated by only 100 m and mapped as the same soil series. The main difference was that soils in the MP plot had about 5% more clay, on the average, than the MA plot, which corresponded with noticeably higher soil-water contents. For this reason slightly different parameter values were used for the two plots.

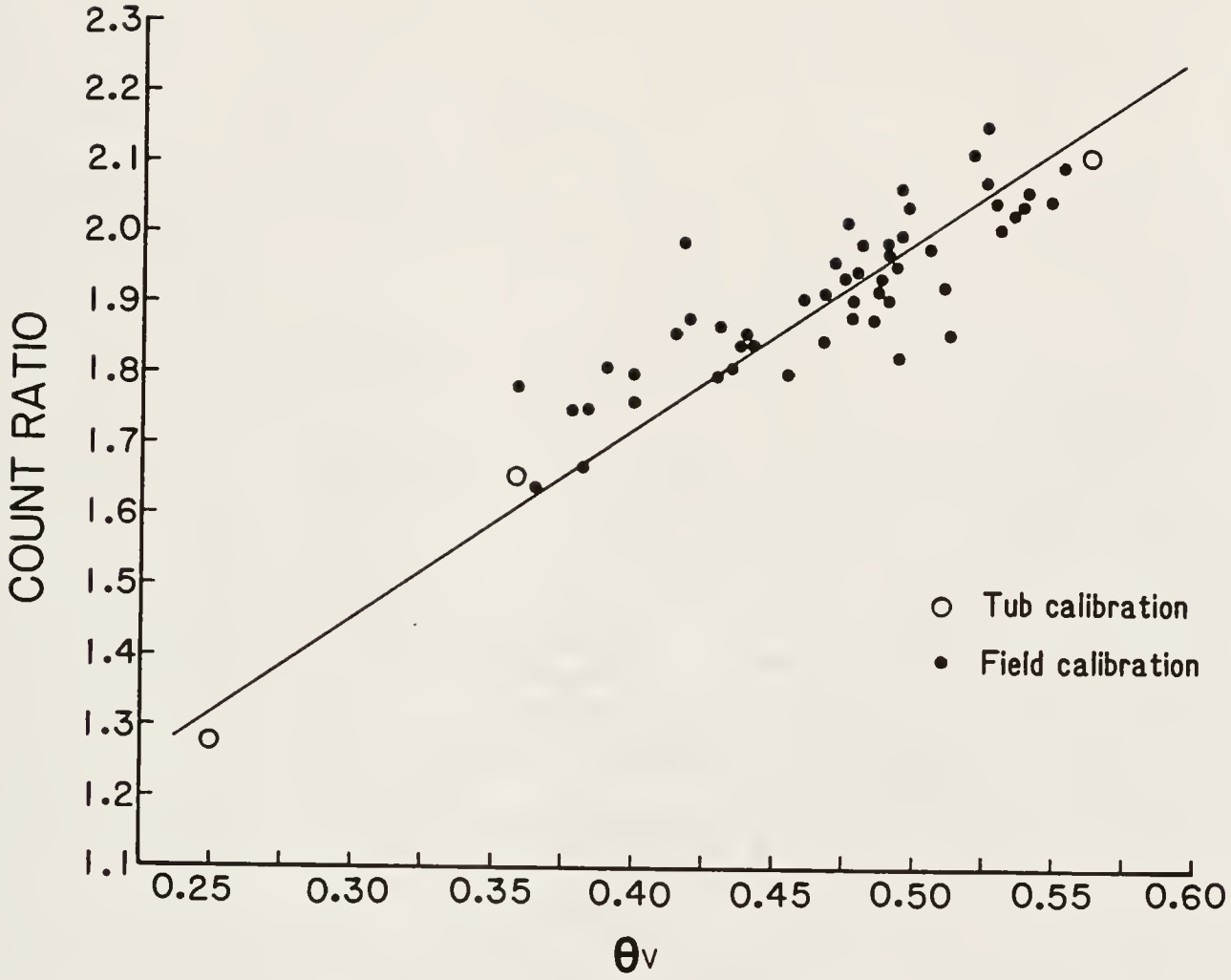

Figure 3-2. The relationship between neutron probe count ratio and soil-water content used to calibrate the probe. The regression equation was; count ratio = 2.69 Θ + 0.65, with r^2 = 0.993.

The soil parameters required to calculate infiltration, drainage, and movement of the solute front in depths above the HWTI are Θ_{inf}, Θ_{fc}, and TRD. Sixteen tensiometers, placed at 15 cm intervals from 10 to 115 cm deep, 2 tensiometers at each depth, were installed in a 3x3 m subplot immediately adjacent to the MA plot. Water was ponded until tensiometers indicated that approximate steady-state flow conditions had been achieved. At that point the subplot was covered with straw mulch and plastic to eliminate evaporation, and changes in soil-water content were monitored with a neutron probe. The value of TRD was estimated as the length of time required for the rate of change of soil-water content to become negligible.

A similar test was attempted in the MP plot but had to be discontinued after large rainfall events caused a rise in water table. The value of Θ_{fc} was estimated as the soil water content at the soil-water tension (cm) equal to the HWTI (also in cm). The soil water characteristic curve under desaturating conditions in two 5.4 cm diameter cores of undisturbed soil from the MP plot was measured for this purpose. The value of TRD was assumed to be the same for both plots. Estimation of Θ_{inf} was based on observation of the soil water content over time in both plots.

Two additional soil parameters are required for calculations within the zone of influence of the water table; the height of water table influence (HWTI), and Θ_{fc}^{*}. Average measured soil-water tensions at two different depths, 75 and

105 cm, were compared with the water table depth. The soil-water tensions were measured with tensiometers at the two plots. In the MP plot there were 10 tensiometers at 75 cm and 5 at 105 cm. There were 9 tensiometers at both depths in the MA plot. The HWTI was taken as the maximum elevation difference for which approximate equilibrium between soil-water tension and the water table could be expected. Values of θ_{fc}^{*} were assumed to vary linearly with the height above the water table as shown in Fig. 1.

Plant Parameter Estimation

Measurements of root weights in the MP system shown in Table 3-1 (Alpizar, personal communication) were used to fit the following exponential relationship of root concentration with depth:

$$\text{Root weight} = 25.179 \exp(-0.067z), \qquad (3\text{-}22)$$

where z is depth (cm). The maximum rooting depth was taken as 70 cm. This rooting depth was assumed to be constant over time.

Table 3-1. Root distribution in the MP plot*.

Depth	Mean Root Weight	Standard Deviation
cm	g cm^{-3}	
0-15	14.0	8.7
15-30	6.4	3.3
30-45	0.4	0.4

*Alpizar (Personal Communication)

No measurements of root concentrations were made in the maize plot. Root distribution with depth over time was calculated from relationships observed by NaNagara et al. (1976) as applied by Davidson et al. (1978). The rooting depth during fallow periods was assumed to be 35 cm.

Estimated PET values were converted to estimates of actual evapotranspiration (AET) using a cropping factor (CF) in the following equation: AET = (CF)(PET). A constant CF value of 1 was used for the MP plot. This consistent with estimates for cacao grown alone (Doorenbos and Pruitt, 1974) and the fact that canopy coverage on the plot was complete.

The CF value for the MA plot varied over time as the maize crop was planted and matured. Estimates of CF during the time that the maize crop was present were taken from Doorenbos and Pruitt (1974), who divided the cropping season into 4 stages with respect to water use. Estimation of CF in the MA plot during fallow periods, which had considerable weed growth, was made by calibration as will be described in the next section.

The amount of water extracted from each layer was calculated using the approach of Molz and Remson (1970). Estimation of soil-water stress was based on the following relationship which is similar to that used by Davidson et al., (1978):

$$AET = AET_{cal}(\Theta-\Theta_{pwp})/(\Theta_{stress}-\Theta_{pwp}), \quad \Theta < \Theta_{stress}, \quad (3\text{-}23)$$

where AET_{cal} is the transpiration calculated in the absence of water stress and Θ_{stress} and Θ_{pwp} are the soil water contents of stress initiation and permanent wilting, respectively.

Calibration/Validation

Soil-water measurements were made periodically with the neutron probe during the calibration/validation period.

There were 5 neutron probe access tubes in each plot. The model output used for these purposes was the profile water content, S. This is defined as

$$S = \int \Theta dz \qquad (3\text{-}24)$$

where z is depth and the lower boundary is at 110 cm. This was calculated from measured Θ values as

$$S = \Sigma \Theta_i \Delta z, \; n=1,7 \qquad (3\text{-}25)$$

where i represents different depth increments, and Δz the increment thickness. As a check on the averaging procedure used, S values determined by gravimetric sampling and neutron probe measurements 18 July were compared.

For logistic reasons, the calibration/validation period was initiated at different dates at the two plots. It started on 14 April in the MA plot and 18 April in the MP plot. These data were used for two purposes, calibration and validation.

The first 18 days of the calibration/validation period were used for model calibration. There was no rain during that time, which was preceded by 3 weeks in which only 4.6 cm of rain were recorded. Thus, DP and P during those 18 days were 0.

Soil-water tensions of greater than 60 kPa by 23 April and changes in S that were less than that expected indicated that the crops on the MP plot probably experienced water stress during the period. The parameters Θ_{stress} and Θ_{pwp} were adjusted to account for this, assuming that changes in S were due to AET. Soil-water tensions on the MA plot were

much lower at that time (about 22 kPa) due to the reduced transpiration of the fallow vegetation. Measured changes in S during this time were used to determine the cropping factor for the fallow vegetation, again assuming that all changes in S were the result of AET. The water stress parameters for the MA plot were taken from characterization data of Aguirre (1971) but were not critical because dry periods did not occur while the maize crop was actively transpiring.

After 2 May there was consistent rain and the conditions of P and DP equal to 0 did not hold. From this point on the calibration ended and measured S values were used to evaluate the accuracy of model calculations.

Simulation

Simulation of water and solute front movement began on 4 Nov. 1982 for the MA plot and 24 Nov., 1982 for the MP plot and ended for both plots on 18 July 1983. Initial soil-water contents were determined gravimetrically. The starting date for the MA plot corresponded to the maize planting date. A second planting of maize in the MA plot took place on 30 May, 1983. All parameter values used in the simulation were determined as described above.

Net Leaching Loss

Net leaching losses over the simulation period were calculated using Eq. 3-2 with the NDP used in place of q and C representing measured soil solution concentrations. Soil solution concentrations of NO_3^-, NH_4^+, Ca^{2+}, Mg^{2+}, and K^+

were measured in extractions from 7.6 cm diameter ceramic porous cup samplers located at a depth of 90 cm. The cups were pretreated in 0.1N HCL prior to installation. There were 9 samplers in the MA plot and 8 in the MP plot. Collections were made at approximately biweekly intervals starting 30 Nov. in the MA plot and 11 Dec. in the MP plot. Samples were collected by applying 40 kPa tension overnight. No collection was made when the soil-water tension was greater than 40 kPa. Concentrations of NO_3^- and NH_4^+ were measured using a steam distillation technique (Bremner, 1965) and the cations were measured by atomic absorption.

Depth of Solute Front

The depth of the solute front movement resulting from application of a nonadsorbed nutrient (e.g., NO_3^-) was simulated for 3 application dates in the MA field plot and 2 in the MP plot. The 3 application dates chosen for the MA plot, 2 Nov., 30 Nov., and 30 May, were actual fertilization dates on that plot. Calculations for the MP plot at the two latter dates were included for purposes of comparison.

Results

Model Inputs

The depth to the water table and measured rainfall amounts over the simulation period are shown in Fig. 3-3. The water table was consistently deeper under the MA plot than under the MP plot. A slight elevation difference between the two plots (the observed water table differences

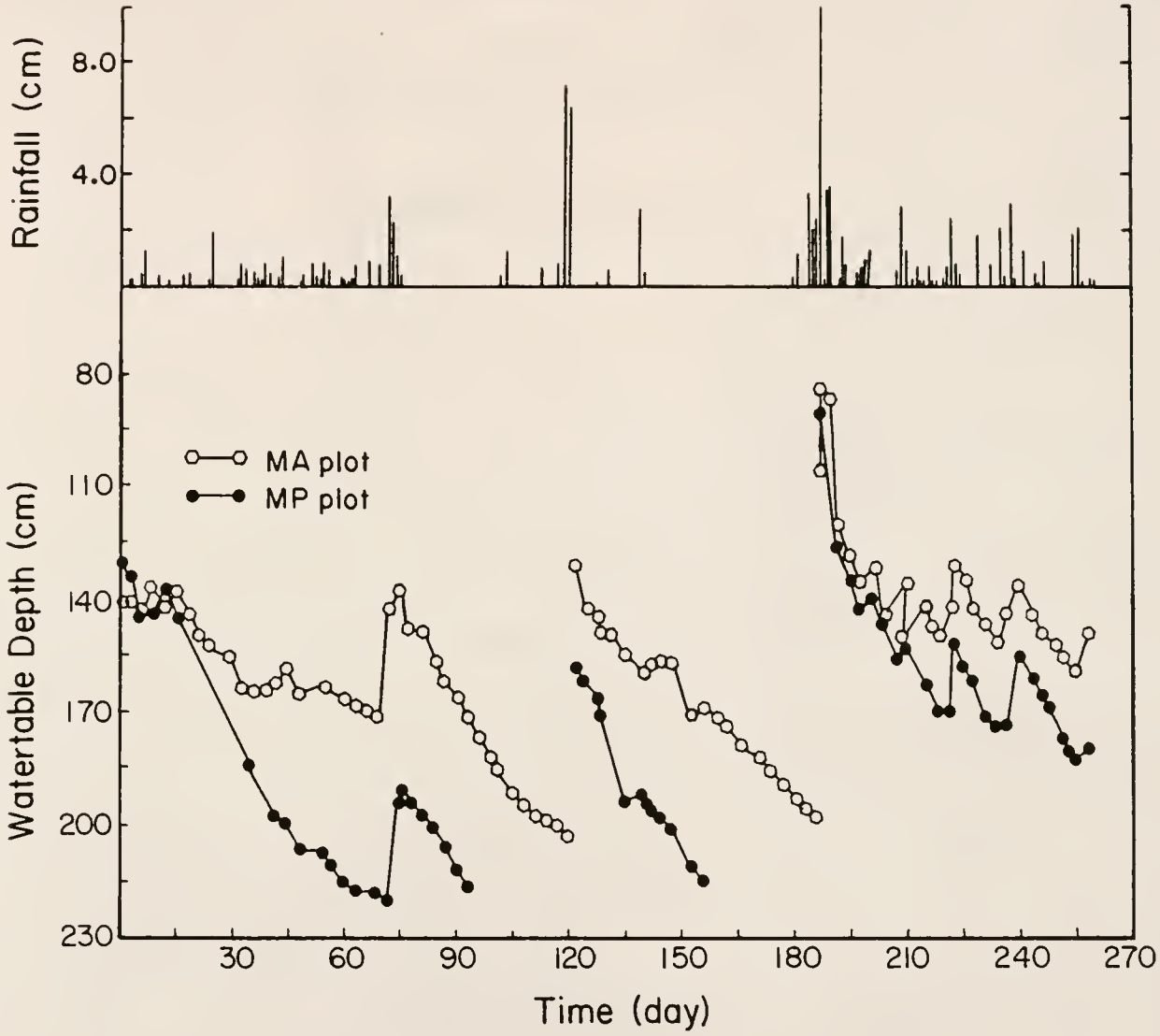

Figure 3-3. Precipitation and water table depth at both plots over the simulation time period (2 Nov., 1982 to 18 July, 1983).

were about 20 cm) and differences in the drainage system at the two plots, explain this. Open ditch drains of 100 to 150 cm depth drained both plots, but the drains around the MA plot had a greater gradient and removed water more quickly to a greater depth. After that depth was achieved, both plots behaved similarly.

The rainfall distribution was fairly uniform during the early portion of the simulation period and was then characterized by two relatively severe droughts. Shortly after day 180 rainfall was consistently high.

Measured pan evaporation varied slightly during the simulation period. It ranged from 0.26 cm day^{-1} in Dec. to 0.48 cm day^{-1} in April. The average monthly pan evaporation over the simulation period was 0.35 cm day^{-1}.

Parameter Estimation

A summary of parameter values obtained is shown in Table 3-2. The change in soil-water tension with depth over time during the determination of Θ_{fc} and TRD is shown in Fig. 3-4. It indicates that the profile is roughly uniform with depth with respect to soil hydraulic properties. The corresponding changes in S are shown in Fig. 3-5. The overall course of drainage is similar to that reported elsewhere in the literature (Hillel, 1980) in that ln S is proportional to ln t. This relationship was approximated using the following parameter values: Θ_{inf} = 0.49, Θ_{fc} = 0.46, and TRD = 5.0 days. The curve calculated using the above parameters is also shown in Fig. 3-5. The calculated

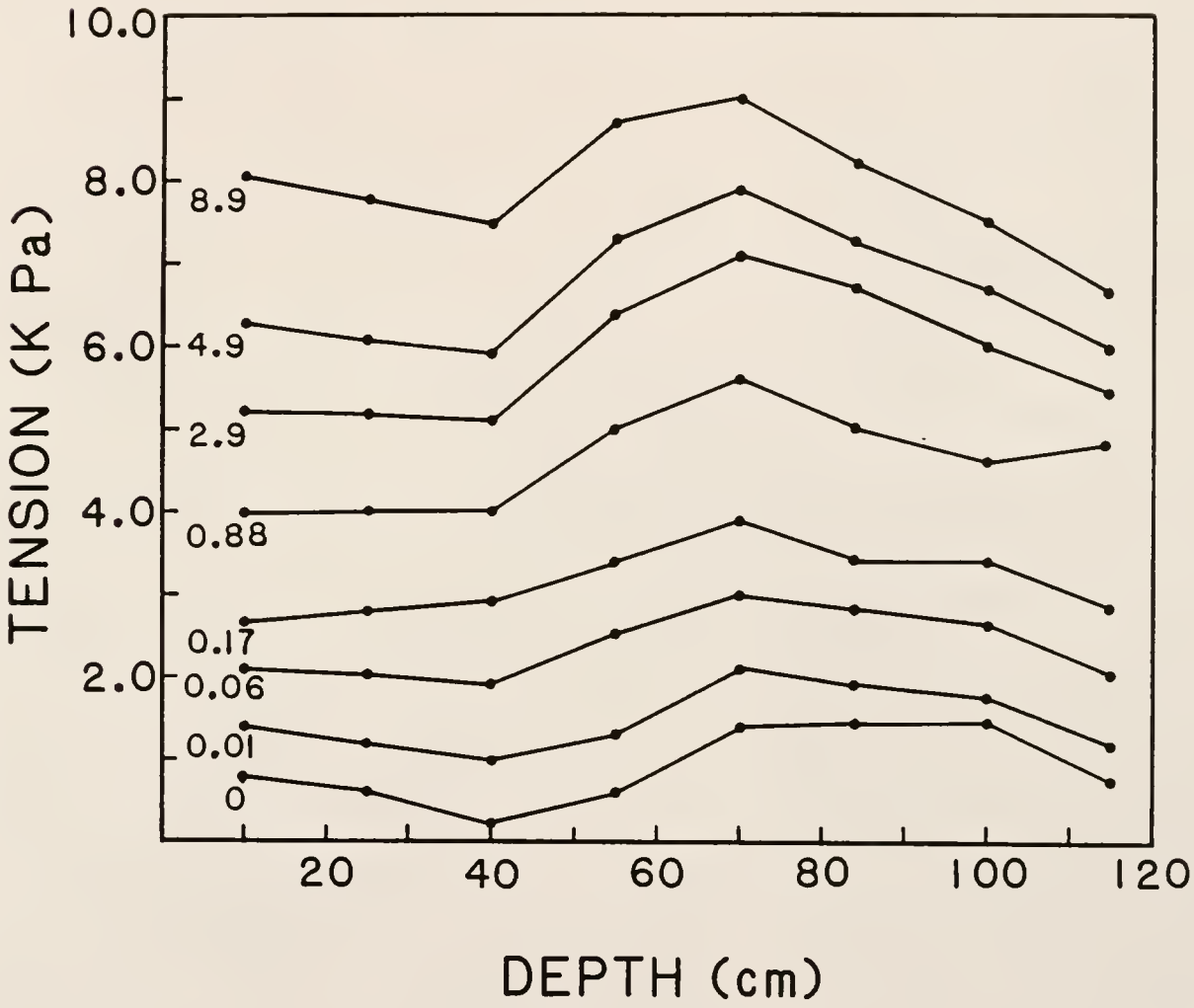

Figure 3-4. Soil-water tension as a function of depth and time after ponding. Time after ponding, in days, is indicated below points representing the upper depth.

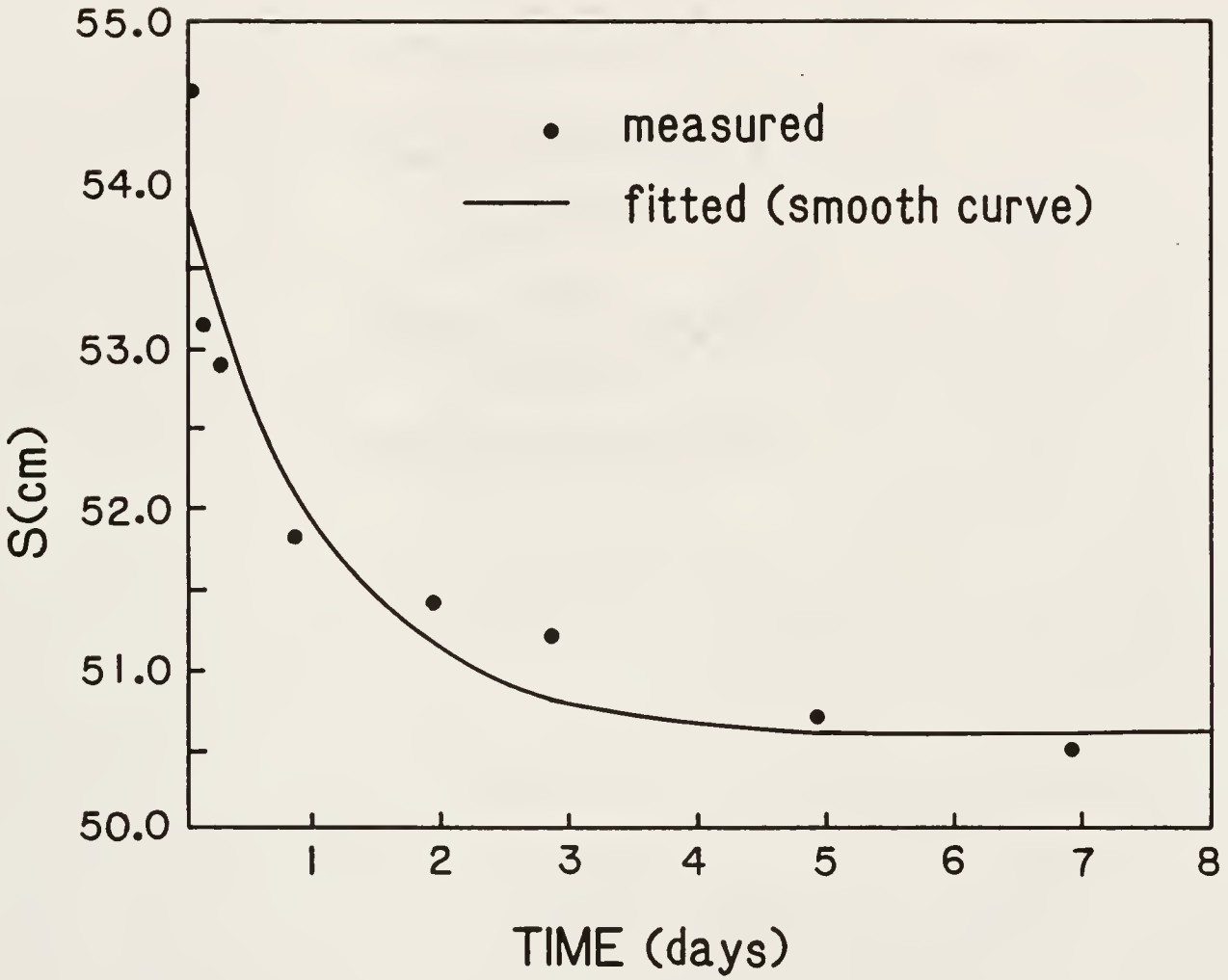

Figure 3-5. Profile soil-water content after cessation of ponding. Fitted values were calculated with model parameters in Table 3-2.

values are close to those measured for times up to 7 days. This is considered to be sufficient because drainage rates for longer time periods are expected to be considerably different due to changes in gradient that result from plant uptake of water and evaporation.

Table 3-2. Summary of model parameter values.

Parameter	Cropping System MA	MP
Θ_{fc}	0.46 (cm cm^{-3})	0.52 (cm cm^{-3})
Θ_{inf}	0.49 "	0.55 "
Θ_{sat}	0.55 "	0.57 "
Θ_{pwp}	0.29 "	0.38 "
Θ_{stress}	0.42 "	0.48 "
TRD	5 (day)	5 (day)
Max. Root Depth	100 (cm)	70 (cm)
CF	variable	1.0

The measured soil water characteristic curves upon which the estimation of Θ_{fc} in the MP plot was based are shown in Fig. 3-6. The value corresponding to a soil-water tension of 5.5 kPa (or 55 cm of H_2O), 0.52, was chosen. The tension of 55 cm H_2O is numerically equal to the value of HWTI chosen (see discussion below). The estimated values of Θ_{sat} and Θ_{inf} are shown in Table 3-2. The TRD was assumed to be equal for both plots.

The average measured soil-water tension and distance from the tensiometers to the water table in both plots are plotted in Figs. 3-7 to 3-10. These plots were used to estimate the HWTI. Each plot is somewhat distinctive, which is due, in part, to the differing conditions encountered at the different depths in the two plots. Recalling Fig. 3-1, the HWTI should be the maximum distance between the water

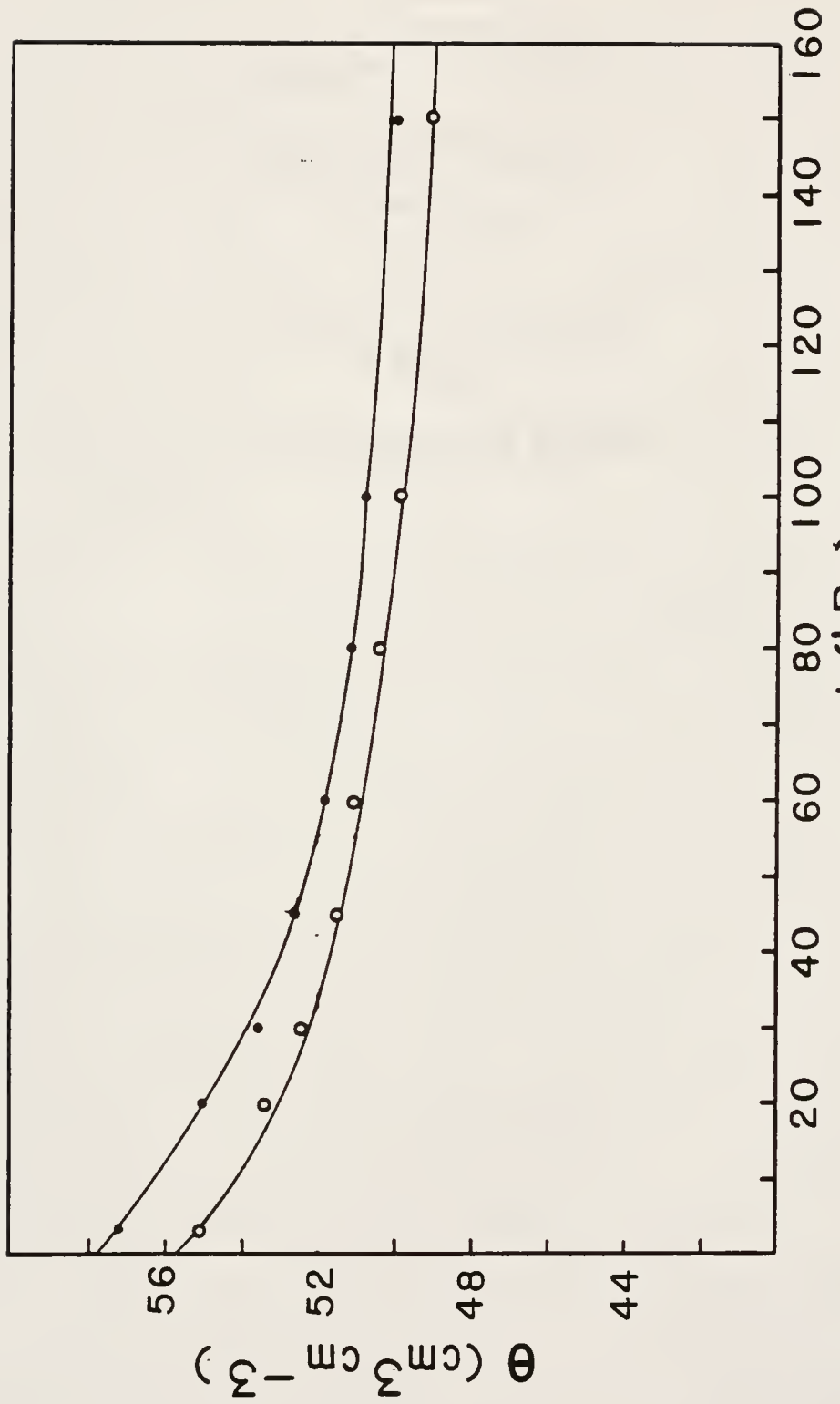

Figure 3-6. Volumetric soil-water content as a function of soil-water tension in two cores taken from the MP plot. The soil-water content at 55 kPa (or 55 cm H_2O) tension is approximately 0.52.

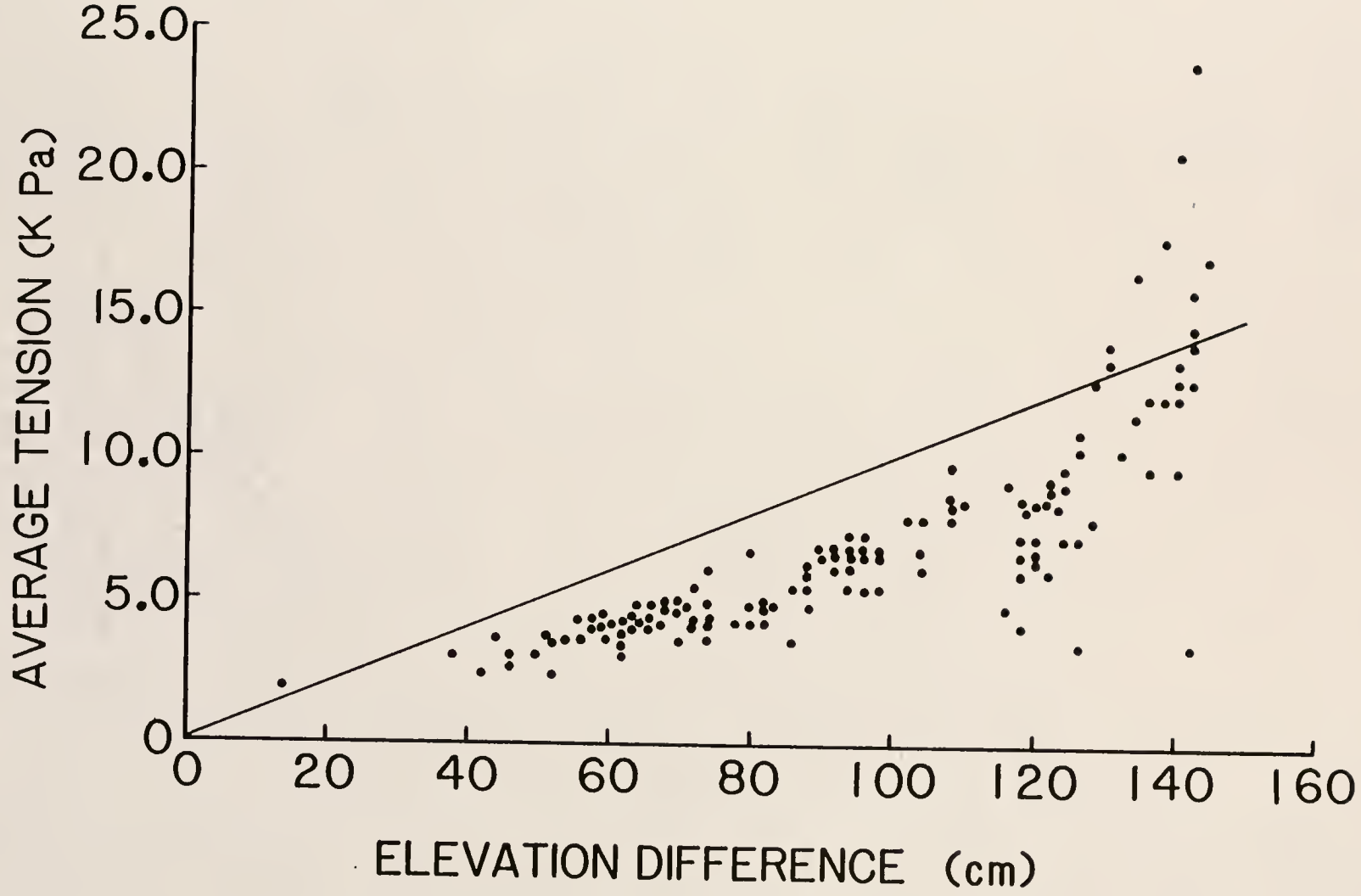

Figure 3-7. The relationship between the average soil-water tension measured with 9 tensiometers at 75 cm depth on the WA plot and the depth to the water table. Elevation difference refers to the distance between the tensiometers and the water table. The straight line represents equilibrium.

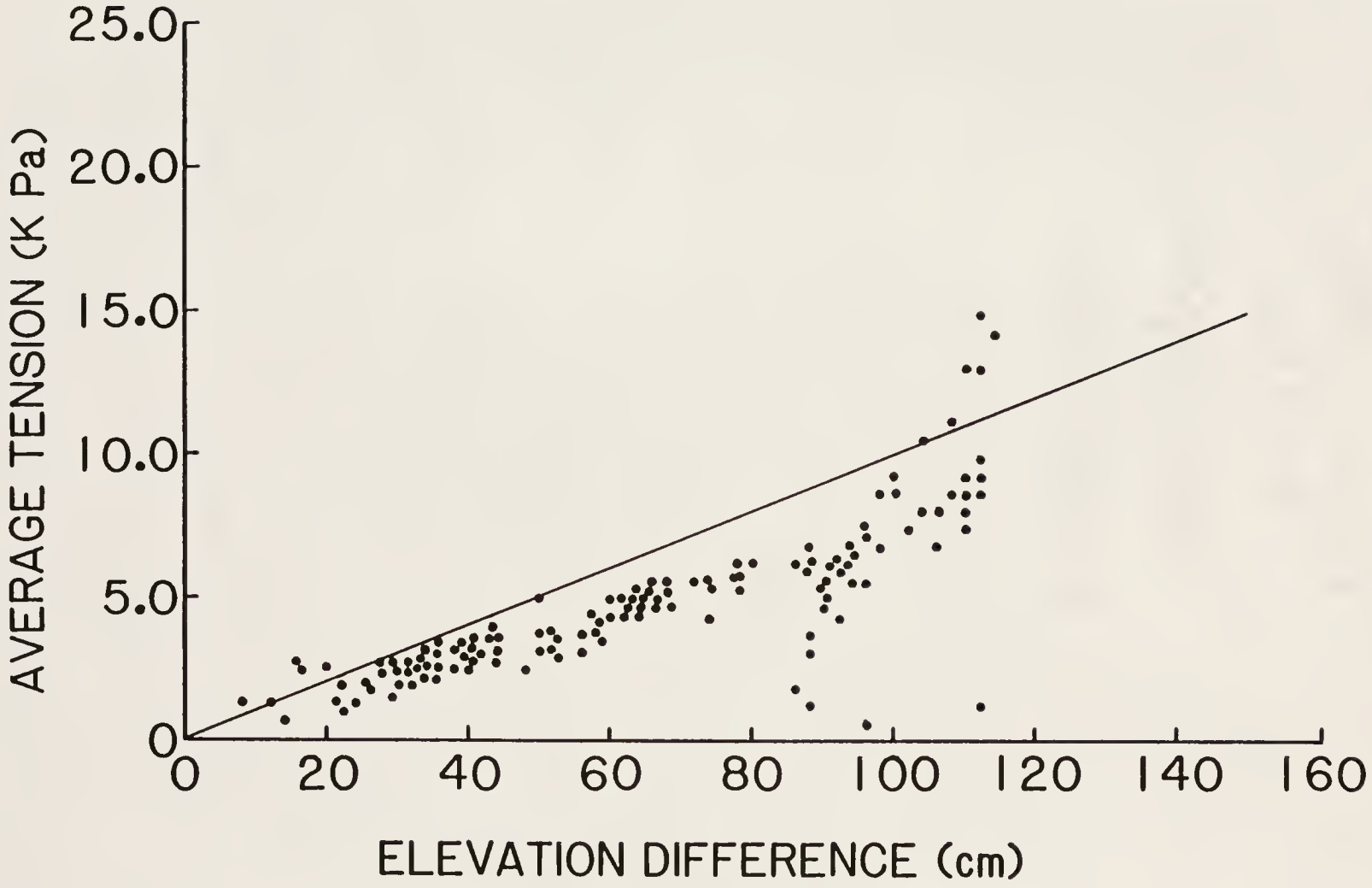

Figure 3-8. The relationship between the average soil-water tension measured with 9 tensiometers at 105 cm depth on the MA plot and the depth to the water table. Elevation difference refers to the distance between the tensiometers and the water tabele. The straight line represents equilibrium.

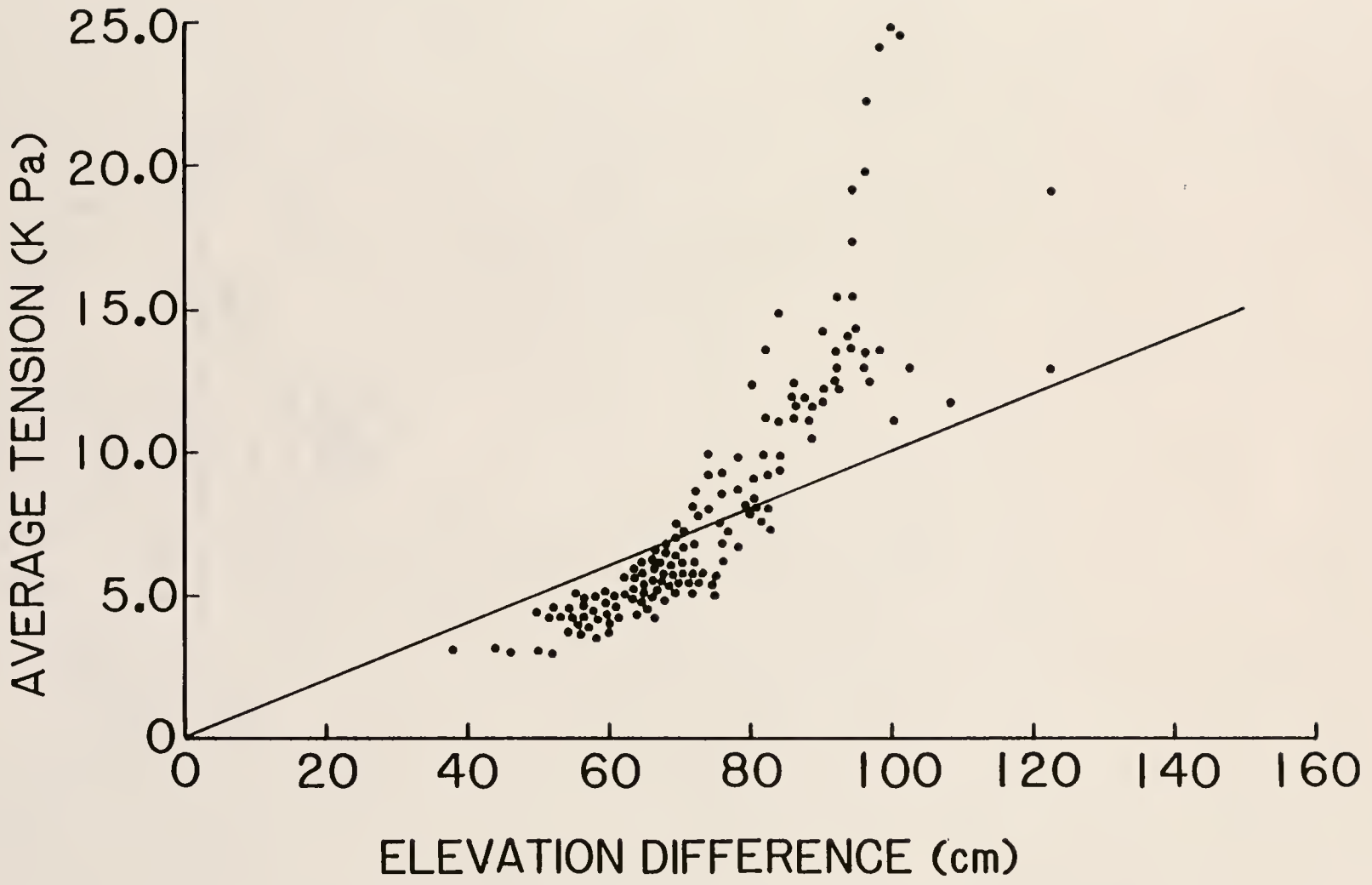

Figure 3-9. The relationship between the average soil-water tension measured with 10 tensiometers at 75 cm depth on the MP plot and the depth to the water table. Elevation difference refers to the distance between the tensiometers and the water table. The straight line represents equilibrium.

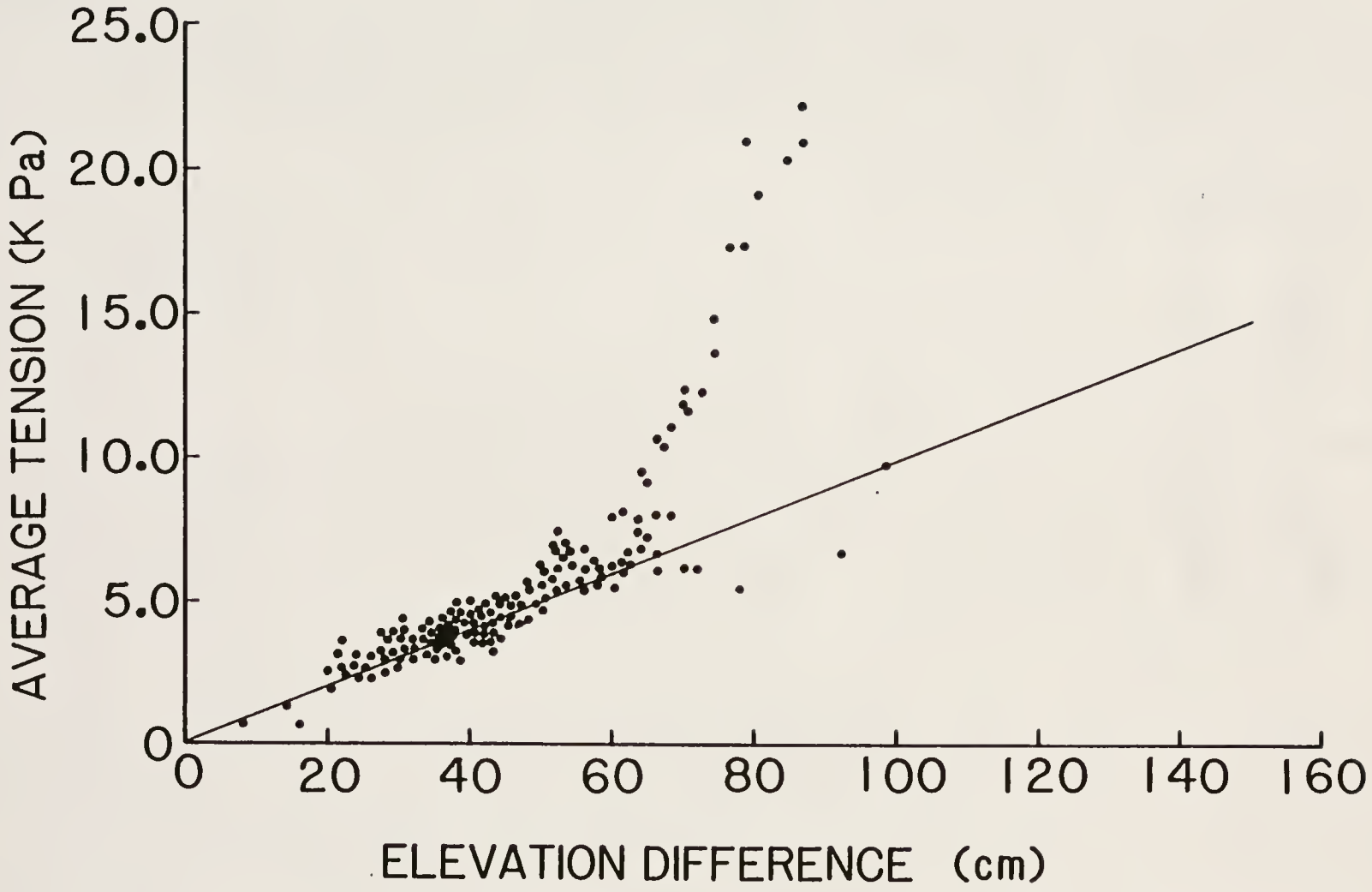

Figure 3-10. The relationship between the average soil-water tension measured with 5 tensiometers at 105 cm depth in the MP plot and the depth to the water table. Elevation difference refers to the distance between the tensiometers and the water table. The straight line represents equilibrium.

table and tensiometers at which equilibrium can be assumed. When that distance is greater than the HWTI, soil-water tension could either be greater than equilibrium due to ET, or it could be less, due to the attainment of field capacity or infiltration. Of course, equilibrium values could also be observed.

Considering the errors that could be introduced by varying elevations within the plots and the accuracy with which measurements were made, reasonable estimates of HWTI range from 45 to 65 cm. A value of 55 cm was chosen for HWTI for modeling purposes, which should be approximately correct in all cases. This value agrees reasonably well with the tension measured at the plots after 5 days drainage (Fig. 3-4). Discrepancies on the order of 1 to 2 kPa are not considered important because they have little effect on estimated Θ values (Fig. 3-5). Although the tension at field capacity is somewhat lower than commonly assumed, it is similar to values measured in other studies (Wierenga, 1985).

Calibration/Validation

As a check on the overall averaging procedures used to calculate S in the field from measured Θ values, S calculated from Θ measured gravimetrically was compared to S calculated from Θ measured with the neutron probe. The results shown in Table 3-3 indicate good agreement.

Table 3-3. Comparison of profile water contents measured gravimetrically and with the neutron probe.

	MA Plot				MP Plot			
Method	Ave.S	S.D.	C.V.	n	Ave.S	S.D.	C.V.	n
	cm				cm			
Grav.	50.99	2.30	0.045	9	55.48	2.59	0.047	5
Probe	50.79	0.73	0.014	4	56.62	1.76	0.031	4

The value of CF on the MA plot during the fallow period obtained by calibration was 0.5. This value was used in the remainder of the validation run and in the subsequent simulation run for fallow periods. The other values obtained by calibration were Θ_{stress} and Θ_{pwp} for the MP plot (Table 3-2).

Measured values of S over time in both plots are shown in Figs. 3-11 and 3-12 along with simulated results. There was close agreement between simulated and measured values on both plots. The variability of S estimation as indicated by the 80 and 90% confidence intervals (vertical bars in Figs. 3-11 and 3-12) in the MA and MP plots, respectively, was rather high. This was not due to high variability per se (the coefficient of variation ranged from 1 to 5%), but to the limited sample numbers. Efforts to improve that condition were hampered by defective aluminum tubing.

Soil Solution Concentrations

Measured soil solution concentrations over time under the two cropping systems are shown in Figs. 3-13 and 3-14. In general, the concentrations under the MA system are at the lower end of the range reported by Barber (1984) for concentrations in the surface horizons of Midwestern soils. By that standard, the concentrations in the MP plot were

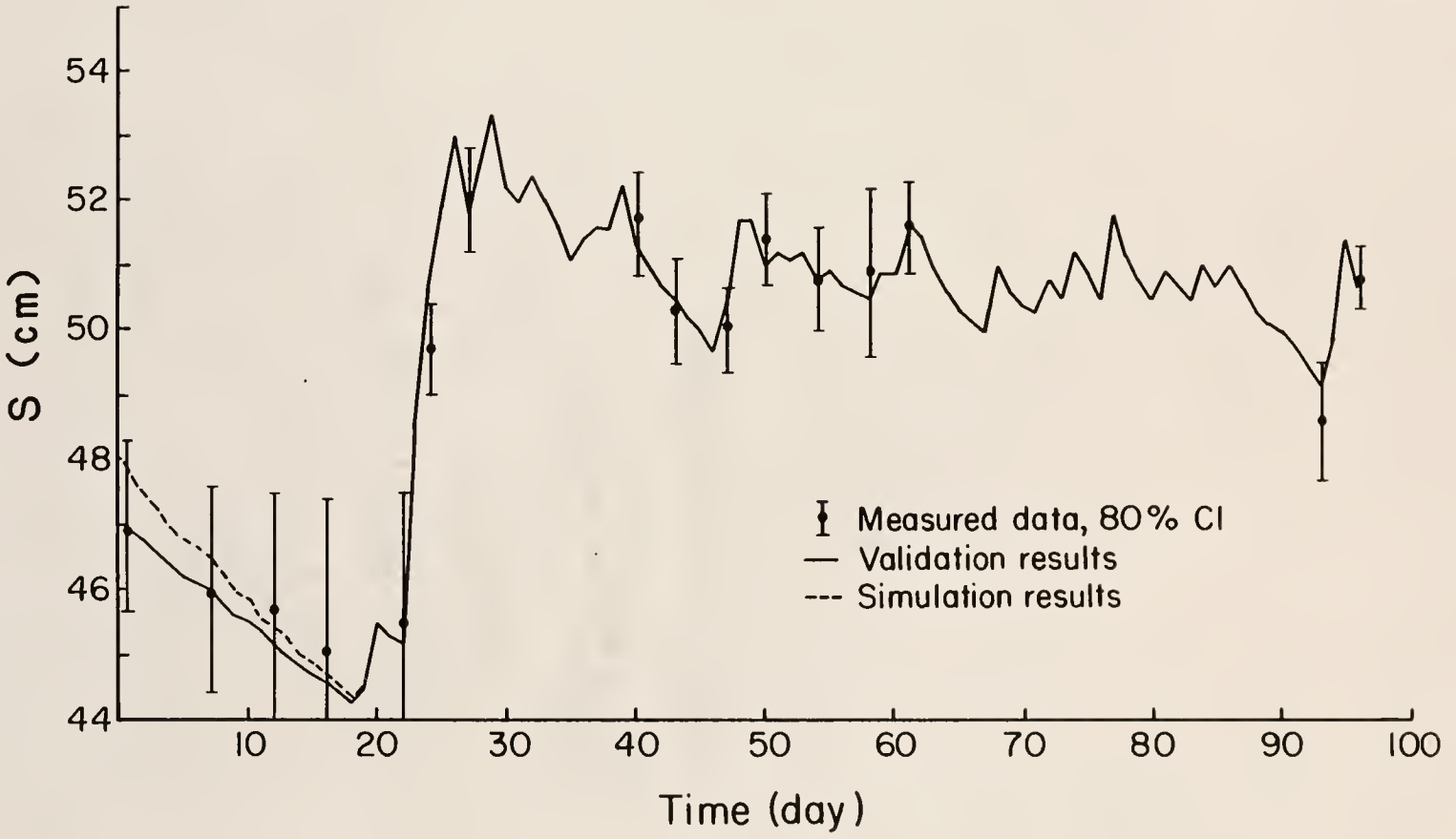

Figure 3-11. Comparison of profile soil-water contents in the MA plot measured over the validation period commencing in April and those computed from initial conditions in November.

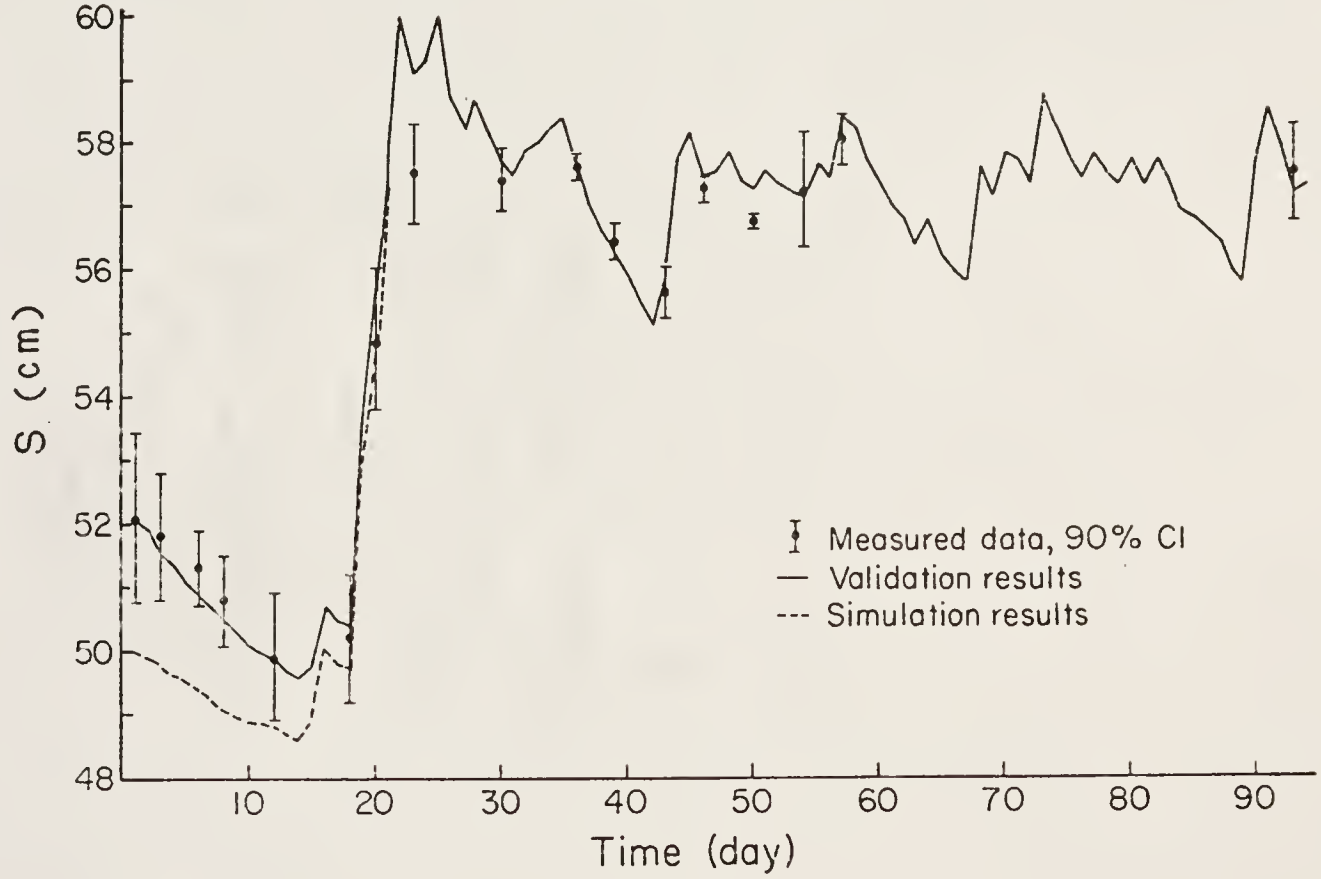

Figure 3-12. Comparison of profile soil-water contents in the MP plot over the validation period commencing in April and those computed from initial conditions in November.

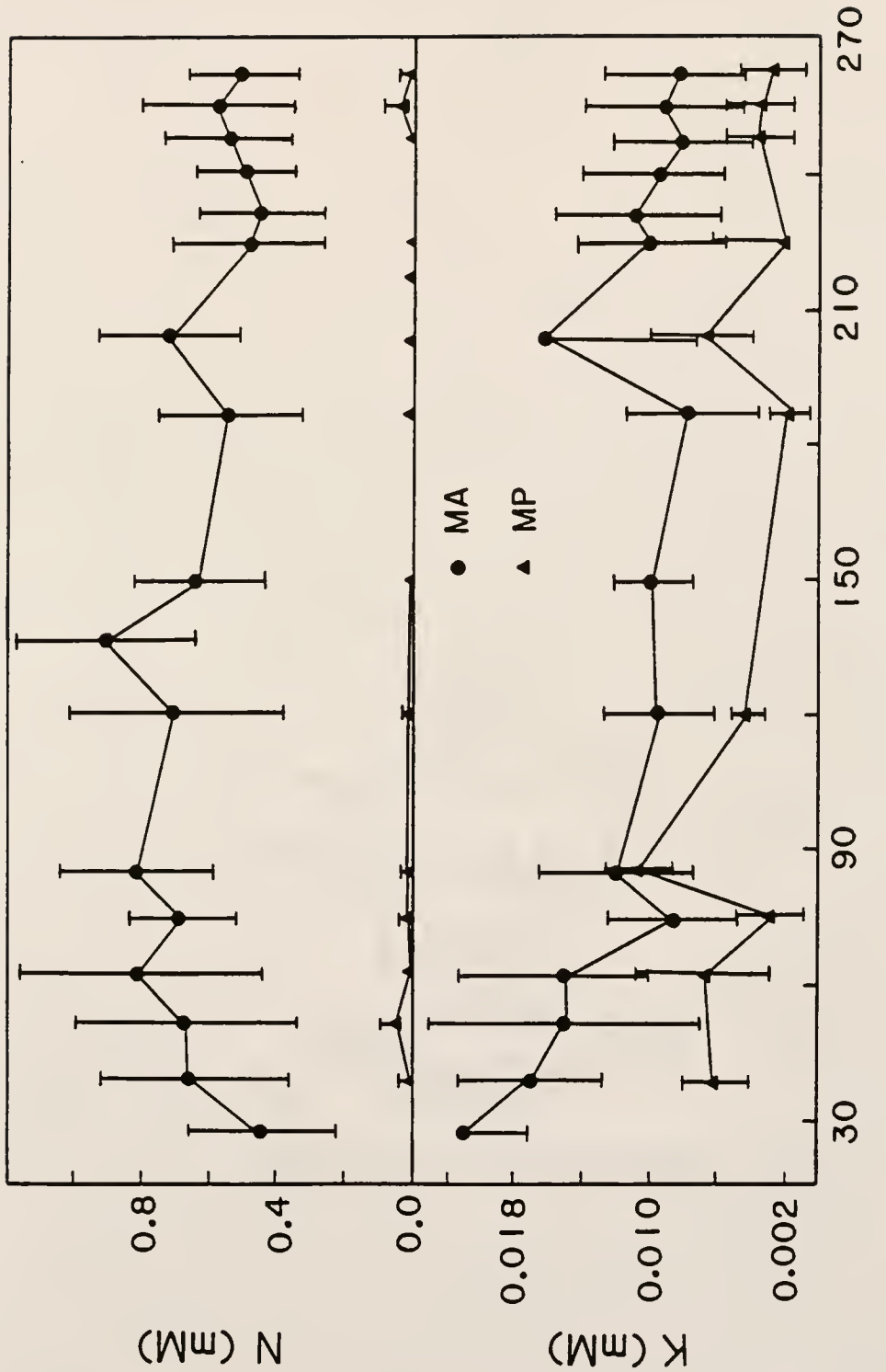

Figure 3-13. Changes in soil-solution concentration of N and K^+ during the simulation period for both plots. The vertical bars indicate the 90% confidence interval.

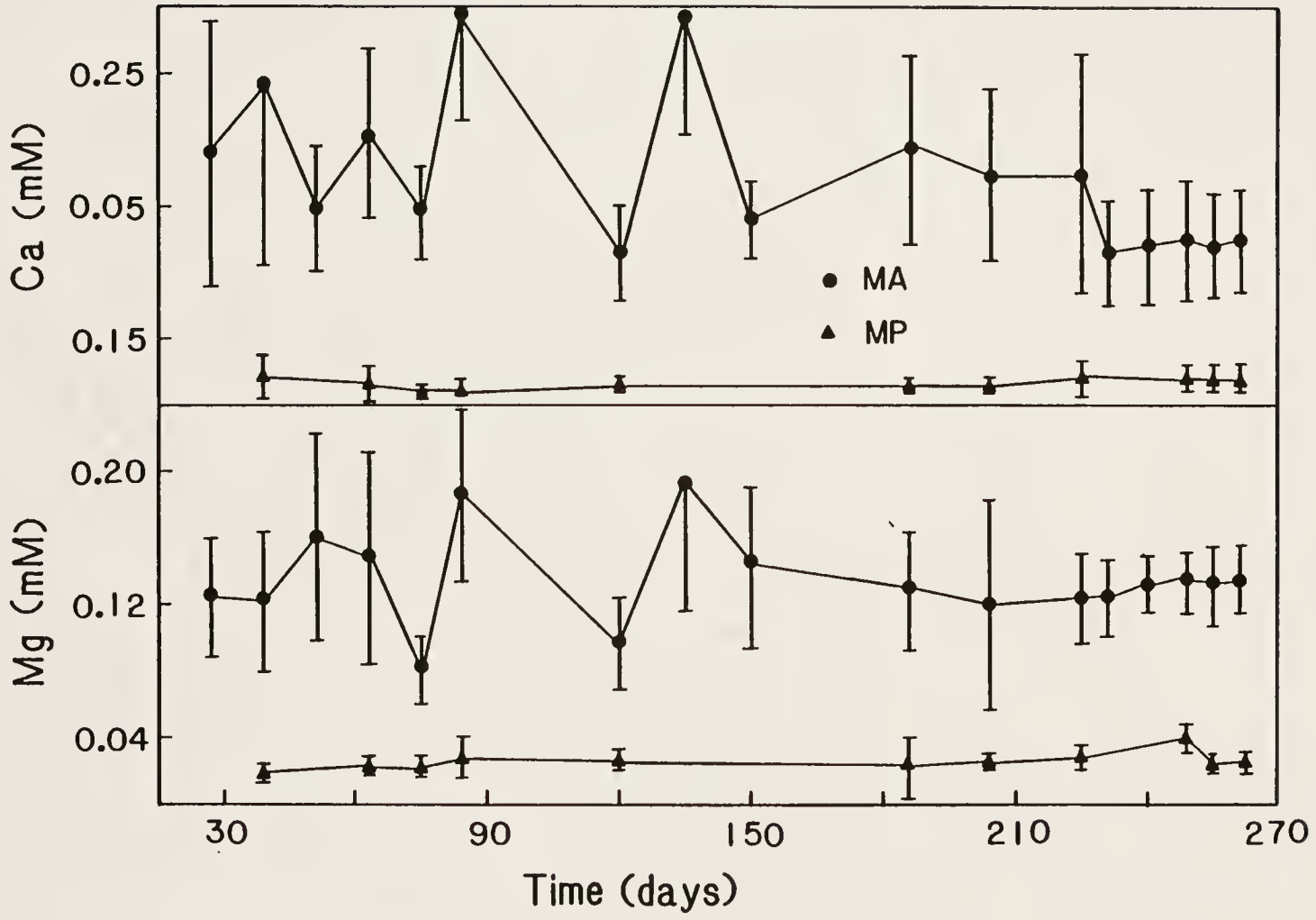

Figure 3-14. Changes in soil-solution concentrations of Mg and Ca during the simulation period for both plots. The vertical bars indicate the 90% confidence interval.

quite low for all ions except K^+. Concentrations of NH_4^+ were relatively low under both systems and were not included because the concentrations measured were generally at or below the minimum concentration required for accurate determination for the methods of analysis used.

With the exception of K^+, soil solution concentrations under the MA plot were clearly greater than those under the MP plot. Even in the case of K^+, the soil solution concentrations in the MP plot were consistently lower than those in the MA plot.

Examination of the concentrations and the associated 90% confidence intervals, suggests that the concentrations were fairly constant over time. Analysis of variance indicated that there was no significant difference (α=0.9-0.99) between the mean concentrations measured on each plot for all ions measured except NO_3^- on the MP plot. This indicates that the means can be pooled. The overall means and pooled standard deviations are shown in Table 3-4. Comparison of the means of the ions in the different plots were significantly different (α=0.99) for K^+, Ca^{2+}, and Mg^{2+}. The concentrations of NO_3^- in the MP plot were more than one order of magnitude less than in the MA and frequently below the accurate detection level of 0.011 mM.

Table 3-4. Average soil solution concentrations.

Nutrient ion	Cropping System MA Ave.	MA S.D.	MP Ave.	MP S.D.
	----------mM----------			
NO_3^-	0.62	0.349	*	
K^+	0.11	0.074	0.043	0.028
Ca^{2+}	0.16	0.104	0.016	0.010
Mg^{2+}	0.13	0.057	0.024	0.006

*Could not be pooled.

Simulation

Values of S calculated for the simulation period are also shown in Figs. 3-11 and 3-12. After approximately 150 days of simulation, calculated values agreed well with those measured. The relatively low S values calculated for the simulation run were probably due to one of two causes: either the AET in the dry period prior to the calibration/validation period was overestimated due to the fact that the laurel trees shed their leaves during the dry season, or there was unaccounted upward movement of water prior to that time.

The greater AET from the MP plot (3-5) was due to the fact that transpiration from that plot was continuous. This resulted in simulated differences in NDP (Table 3-5).

Net Leaching Loss

The net leaching loss (NLL) of the four elements measured were calculated by multiplying the NDP and the average soil solution concentration. The results are shown in Table 3-5. These results are for a time period somewhat less than one year, which makes direct comparison with most other measured results difficult. The range of values

reported, however, is so great that these values easily fall within it (Sanchez, 1976). From an agronomic viewpoint, the loss of NO_3^--N in the MA plot is clearly important.

Table 3-5. NDP and Net Leaching Loss Values.

Calculated Value	Cropping System	
	MA	MP
AET	45 (cm)	55 (cm)
TR*	111 (cm)	111 (cm)
NDP	66 (cm)	57 (cm)
NLL N_+	57 (kg/ha)	1 (kg/ha)
K^+	3 (kg/ha)	1 (kg/ha)
Mg^{2+}	21 (kg/ha)	3 (kg/ha)
Ca^{2+}	43 (kg/ha)	3 (kg/ha)

*TR is the total rainfall during the time of comparison.

Depth of the Solute Front

The simulated movement of a nonadsorbed solute front is shown in Fig. 3-15. The rate of movement from the third application is considerably greater than that from the first. Movement is clearly related to patterns of rainfall.

Note that the DSF from the first two applications tend to converge with time. Also note that little residual effect of fertilizer can be expected between the two applications as the front has moved well beyond 110 cm depth before the second planting. The difference between the MP and MA plot is ascribed to the greater AET from the MP plot.

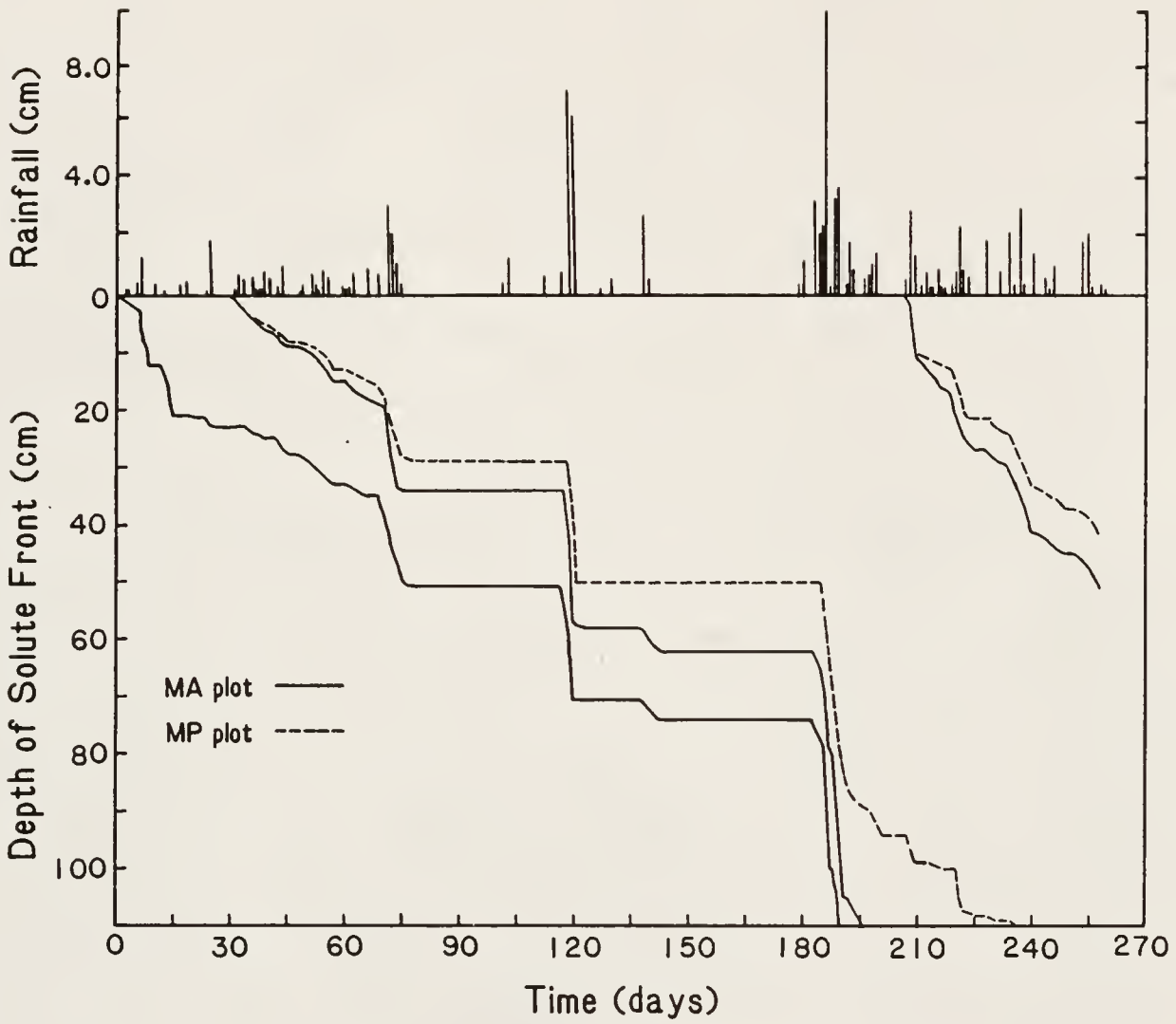

Figure 3-15. Depth of solute front movement resulting from application of a nonadsorbed solute on days 1, 30, and 207 in the MA plot and days 30 and 201 in the MP plot.

Discussion

Parameter Estimation

Two aspects of the methods of parameter estimation bear discussion. The first is that, with the exception of parameters related to fallow periods in the MA plot and water stress in the MP plot, all parameter values were estimated prior to simulation. In other words, the values used are not "best fit" parameters. The goodness-of-fit obtained by such values is encouraging.

The second aspect is that the chosen parameter values have essentially no statistical validity and were, in most cases, made subjectively. This is a common practice in studies employing capacity parameter-based models (Rose et al., 1982a; Barry et al., 1985). It carries with it the two assumptions that: (1) the parameters do not vary greatly in the field, and (2) the desired model output is not very sensitive to parameter selection. In fact, the ultimate utility of this kind of approach is dependent on the above conditions.

One of the principal advantages of using capacity parameters is that, in concept, a field or plot can be unambiguously represented by a single value. The value of S at a given time, for example, is simply the integral of Θ over the volume of soil in the system of interest. The significance of this is that the value of parameters can be bracketed. It is clear, for example, that Θ_{fc} must be less than Θ at saturation. Similarly, it is not difficult to

establish minimum values from examination of Θ in the field drainage patterns and moisture release curves. This reasoning also applies to the other soil parameters. Thus, although information on the precision and accuracy of parameter estimations is lacking in this study, it is possible to have confidence in the bounds of those values.

The accuracy of the parameter values used can be evaluated on the basis of the sensitivity of desired outputs to variations of parameter values. There are two outputs desired from the model in this study. The first is the NDP, which was used to calculate net leaching losses. The second is the DSF, which is included to illustrate the movement of solutes through the two systems.

Calculation of NDP

The fact that NDP (=DP-UP), rather than DP, was calculated should be recognized. This is because parameters related to water stress and transpiration during fallow periods were obtained by calibration. The calibration was performed during an extensive dry period. At that time, P and DP were 0. Under this condition DS=UP-AET. Since UP was not considered in model calculations, AET values calibrated under these dry conditions, when UP should be greatest, was actually a lumped term that implicitly included UP.

The drop of the water table in both plots after major rainfall events was generally rapid (Fig. 3-3) so that it was below about 170 cm by the time the upper portion of the soil profile had dried enough to create an upward gradient

for soil-water flow. This suggests that UP was not large. Clearly, it was small relative to DP, since rainfall was much greater than PET during the simulation period (Table 3-5). In terms of net leaching loss calculation, NDP should be the preferred parameter.

Given the approach to water movement used, the value of NDP is ultimately calculated from Eq. 3-5 (note that ET in Eq. 3-5 is replaced by AET). From this equation it is clear that the accuracy of NDP calculation is dependent on the accuracy of P, AET, and DS. The calculation of S depends on several parameter values, including HWTI, Θ_{fc}, and TRD. The possible values of S are bracketed, however, by Θ_{fc} and Θ_{pwp}. The difference between S at those two soil-water contents represents the maximum contribution to NDP possible from the DS term. Since neither extreme value was encountered in the field, the contribution was much less than that. This value is fixed and, whatever its magnitude, must eventually become small relative to P and AET, both of which accumulate over time. Thus, for long time periods, the DS term, and therefore the parameters used to calculate it, become increasingly unimportant to the calculation of NDP.

Precipitation was measured at the site and is generally taken as a given. Some error is introduced in this way when a plant canopy is present because it retains some of the incoming rain thereby reducing the actual amount of rain entering the soil. This effect is balanced somewhat by the reduced AET that results.

Estimations of AET were based on measured evaporation from a class A USWB pan. The accuracy of this method is somewhat dependent on the climate and quality of pan monitoring (Jensen, 1973). Climates characterized by low radiation winters and frequent hot dry winds are least conducive to the use of the pan (Jensen, 1973). On the other hand, the method has been very successful in humid tropical regions (Chang et al., 1963). According to Jensen (1973), the class A pan should be accurate within $\pm$ 10% with proper management, which is of an accuracy comparable to that of other estimation methods. This is important from a practical standpoint because further improvement (e.g., by use of lysimeters) requires considerable expense and effort.

Table 3-6 illustrates the relative effects of varying selected parameter values as compared to a $\pm$ 10% change in pan factor (k) used to calculate PET for the 98 day validation simulation for the MA plot. Over this time period the $\pm$ 10% variation in pan factor had a greater impact on NDP calculations than alterations of the other parameters within the the likely range of values. This effect is expected to be greater over longer simulation periods, as explained above. Also note that the alteration of the HWTI had no effect on S at the end of the simulation period or on NDP. This will be true of all simulations with the model in which either the final water table depth is equal to the initial depth, or the the water table depth at both times is below the depth of interest by HWTI cm. The impact of water table

depth in the model is to elevate S calculations when the water table is high and to temporarily slow the rate of solute movement through the system.

Table 3-6. Sensitivity of Model Output to Variations in Critical Parameters.

Parameter Altered	Value		AET	S*	NDP
			----------cm---------		
none	---		16.1	50.7	46.4
k	0.9		18.0	50.6	44.6
k	0.7		14.2	50.8	48.2
Θ_{fc}	0.475	(cm^3 cm^{-3})	16.4	51.8	44.9
Θ_{fc}	0.445	"	16.1	49.7	47.4
HWTI	0.70	(cm)	16.1	50.7	46.4
HWTI	0.45	"	16.1	50.7	46.4
TRD	4	(days)	16.1	50.5	46.5
TRD	6	"	16.1	50.8	46.2

*The S value at he end of the calibration/validation period.

Depth of Solute Movement

The calculation of DSF is dependent on fluxes within the soil profile and the value of Θ_{fc}. Both the amount of input to soil layers during redistribution (Eq. 3-9) and the change in solute front depth from a given input (Eq. 3-8) are largely dependent on the value of Θ_{fc}. From Table 3-5 it is clear that the calculation of S is relatively sensitive to Θ_{fc}. The good agreement between measured and calculated S values indicates that Θ_{fc} is reasonably well estimated.

The solute front is conceived, in an ideal sense, as the leading edge of the solute "pulse" that would result from soluble fertilizer application. From column and field experiments it is clear that hydrodynamic dispersion and diffusion cause a spreading of the idealized pulse over

depth. As the pulse travels through the profile this spreading will increase and the original, sharp pulse, becomes increasingly less well defined. This effect is accentuated by plant uptake, which reduces the height of the pulse above backround levels. When the DSF crosses a particular depth, therefore, a large portion (>50%) is expected to be above that location and the remainder below. Even so, it appears that little of the applied fertilizer is expected to be carried over to subsequent crops in the MA plot.

Also note that, as time (or DSF) increases, the position of the DSF from different application times tends to converge. Thus, the pulses from different application times tend to become indistinguishable.

The patterns of solute movement over time in the two plots are quite distinct. Solutes move through the MP profile more slowly than through the MA plot. Two factors are responsible for this difference; the greater AET and Θ_{fc} in the MP plot. This slower movement reduces the likelihood of leaching because the crop has a greater opportunity to use the nutrient.

Soil Solution Concentration

Two aspects of the soil solution measurements were noted previously: (1), the relative uniformity of solution concentrations over time and (2), the difference in concentration between cropping systems. Both have important implications to the estimation of leaching loss. Three

factors that contribute to the uniformity of soil solution concentrations over time were described above. They are the spreading of solute pulses by dispersion, the reduction of peak heights by plant uptake, and the merging of pulses with depth as the DSF increases. To these may be added the effect of relatively slow release of nutrients by mineralization, which will tend to increase the backround "noise" levels.

The relative uniformity of solution concentrations is important because it permits the interpolation of concentration values between measurements with some confidence.

Net Leaching Loss

The errors associated with both the estimation of soil solution concentration and NDP have been discussed. It should be recognized that movement of a solute below 100 cm does not necessarily mean that it is lost from the crop. There is, undoubtedly, some uptake of water and nutrients from below that depth. This quantity does provide a good comparative index that is a good approximation, however.

Penetration of roots to that depth must be short lived on the MA plot, because both the maize crop and the fallow vegetation are short lived. The root systems of cacao, which is the dominant crop in the MP plot, are not expected to feed from deep in the soil profile because cacao plants are mainly lateral feeders and are intolerant of flooded conditions (Smythe, 1966).

System Leaching Loss Sensitivity

Based on the above discussion it is possible to isolate environmental and cropping system properties that may be used to characterize the potential sensitivity of a cropping system to leaching loss. The properties considered here will be restricted to those directly related to water movement.

In these terms, the most important crop property is AET. Although different crops have different propensities for transpiration, from a cropping system standpoint, the longer an actively transpiring crop is in the field, the greater AET and the less the potential nutrient loss by leaching.

The AET must be combined with rainfall to be of use in determining the sensitivity to leaching loss. The net water input to the system is the difference between P and AET. The resultant parameter, the effective precipitation (EP), can be used to approximate the movement of a solute front using the equation

$$DSF \approx EP/\Theta_{fc}. \qquad (3\text{-}26)$$

Calculation of DSF using Eq. 3-26 is accurate only if AET = 0 and the initial soil-water content is Θ_{fc}. When AET > 0, DSF calculated using Eq. 3-26 will be inaccurate for two reasons: (1) water loss by ET is distributed over the entire rooting zone whereas the use of Eq. 3-26 presumes that all ET occurs above the DSF, and (2) the actual effective input from a given precipitation event is somewhat less

than the amount of that event because there is ET during redistribution, which is not accounted for in Eq. (3-26).

The two effects tend to counter each other, but the net effect is generally for Eq. 3-26 to slightly underestimate DSF. If this small discrepancy is acceptable, then it is possible to estimate DSF with climatic data.

The other important component of the system is the soil. Recall that the DSF was calculated using Θ_{fc}. If the entire rooting depth is considered, it is possible to calculate a leaching depth (LD) that is analogous in concept to the pore volume described in the previous chapter. Thus, it is considered to be the volume of water per unit area required to displace a nonadsorbed solute through the crop rooting zone. The leaching depth is calculated as:

$$LD = D\ \Theta_{fc} \qquad (3\text{-}27)$$

where D is the depth of interest (cm), or 110 cm, and LD is in cm. Small changes in Θ_{fc}, such as those between the MA and the MP plots, have relatively little effect on the leaching volume (50.6 vs. 57.2 cm, respectively). The effect of soils can be dramatic when strongly contrasting soils are compared, however. A sand textured soil with a Θ_{fc} of 0.1, for example, has a leaching volume of only 11 cm.

At this point it is possible to combine soil, climate and crop characteristics into a single parameter that characterizes the sensitivity of the system to leaching

loss. This parameter, the solute residence time (SRT) in days, is defined by

$$SRT = LD/EP. \qquad (3\text{-}28)$$

Using mean monthly values of rainfall and pan evaporation provided by Forsythe (1975) it is possible to compare the average residence times for the two plots. Comparisons were made assuming that fertilizer applications were made on 1 Nov. and 1 June, which is usual for the MA plot. The residence times for the MP plot for the two dates of 83 and 97 days are greater than those for the MA plot of 60 and 74 days. Thus, a nonadsorbed solute, such as NO_3^-, is expected to reside in the MP plot about 23 days longer that in the MA plot. The MA plot can therefore be considered to be more sensitive to leaching loss than the MA plot under current management. This partially explains the observed differences in net leaching losses.

The difference in solute residence time is, however, only partly due to the cropping system itself. Part of the reason for it is the greater Θ_{fc} value of the MA plot. When the Θ_{fc} value of the MA plot is used to calculate the SRT in the MP plot, values of 63 and 84 days are obtained, which indicate a much smaller difference.

The reasons that a greater difference was not observed are that: (1) AET in the MP plot was less than the maximum due to reduced transpiration during dry periods, and (2) the transpiration from the MA plot is increased by the weeds in

the fallow periods. It appears that other factors are responsible for the lower leaching losses from the MP plot.

It should emphasized that the SRT as defined above is intended only as a means of characterizing soil-climate-cropping system combinations, not as a means of predicting the actual residence time of a given solute over a specific time period. That requires information concerning the chemical interactions of that solute with the soil and specific weather patterns. The SRT is intended as an index in much the same way that mean annual rainfall is a climatic index.

Summary

There is a relatively high potential for nutrient loss by leaching in humid tropical regions. One way that has been proposed to reduce such losses is to maintain a constant crop cover that will take up water and nutrients continuously. In this study the leaching losses from two contrasting cropping systems managed at approximately the same level were compared. The major objectives were to determine if: (1) leaching losses were different from the two cropping systems and (2) factors responsible for differences could be expressed in terms of simple parameters that could be used to evaluate the sensitivity of cropping systems to nutrient loss by leaching.

A capacity-parameter based model, similar to NITROSIM (Rao et al., 1981), was developed. Additional

considerations were made to include the effects of a fluctuating water table.

Estimation of net leaching loss was based on the net deep percolation calculated with the model and measured soil solution concentration values. Calculated soil profile water contents over a 98 day period closely approximated measured values.

Sensitivity analysis of selected soil parameter values and actual evapotranspiration indicated that the $\pm$ 10% accuracy in estimates of actual evapotranspiration was the main limitation to the accuracy of net deep percolation estimation.

Soil solution concentrations of NO_3^-, NH_4^+, K^+, Ca^{2+}, and Mg^{2+} were monitored. The concentration of NH_4^+ was too low in both cropping systems to contribute to leaching loss. This was also true of NO_3^- in the mixed perennial cropping system. Soil solution concentrations of the other ions were significantly greater, by a factor of 2 to 15 times, in the monocropped annual system. The estimated loss of NO_3^--N over a 250 day period was 56 kg/ha.

The movement of applied nutrients was illustrated for the case of a nonadsorbed solute like NO_3^- by calculating the movement of the solute front. These calculations indicated that, for the conditions encountered, little residual fertilizer effect could be expected in the monocropped annual system. Movement of ions in the mixed

perennial system was somewhat slower, due to both greater transpiration and higher field capacity values.

The two systems were characterized in terms of sensitivity to leaching using the residence time of a nonadsorbed solute as an index. Slightly greater residence times were calculated for the MP system, indicating that it is less sensitive to leaching loss than the MA system. This difference is largely due to differences in Θ_{fc} between the two plots. On this basis it was concluded that differences in soil solution concentrations were due to additional factors, such as the amounts of nutrients applied and the crop demand, as well as water use patterns.

CHAPTER IV
MATHEMATICAL DESCRIPTION OF NITROGEN MINERALIZATION DURING INCUBATION

Introduction

This study is part of a larger project investigating the movement of nutrients in different cropping systems found in Costa Rica. In many of those systems the mineralization of soil organic N contributes a major portion of crop needs. The movement of nutrients through the rooting zone is partially dependent on the timing of their entry into the soil solution. It is important, therefore, to establish some means of estimating amounts and rates of mineralization.

Despite the long recognized importance of N mineralization to crop performance and waste disposal, a widely accepted measurement method has not been developed (Keeney, 1982; Stanford, 1982). Problems of measurement stem partly from the fact that both the N source (soil organic N; plant and animal residues) and the microbes that mineralize N are poorly characterized. This situation is exacerbated by the fact that a number of soil and environmental conditions control the rates and products of mineralization.

Field methods, which attempt to use the ambient soil and environmental conditions and microbial populations have been used but require a certain degree of disruption of the soil and are lengthy and labor intensive. Most laboratory

methods use either chemical (extraction) or biological (incubation) methods to isolate a fraction of soil organic N which is then compared and indexed to some measure of N mineralization. For these laboratory approaches to succeed three conditions must be met. First, there must be some fraction of the total soil organic N that is significantly more mineralizable than the rest of the soil organic N. Second, the extraction procedure must consistently isolate a fixed portion of this N. Third, the kinetics of mineralization, which are sensitive to soil and environmental conditions, must be accounted for. The first condition is assumed and is fundamental to the approach. The second and third conditions are usually approached empirically through some type of calibration procedure (Stanford, 1982).

Models of N Mineralization

First Order Kinetic Model. Stanford and Smith (1972) proposed a laboratory method that generated a great deal of interest in the assessment of soil organic N availability. The method calls for aerobic incubation of soil under optimal conditions with periodic leaching and measurement of inorganic N in the leachate. While this method has received widespread use, its primary advantage is in the way the data generated are analyzed. Specifically, two assumptions were made which enable the calculation of the actual amount of N mineralized over time thereby bypassing the need for calibration which has proved problematic. This combination of

assumptions and mathematical analysis constitutes a simple model for the mineralization of N.

The two basic assumptions made by Stanford and Smith (1972) were that: (1) there is a more or less distinct, homogeneous pool of soil organic N that mineralizes with sufficient rapidity that other sources may be ignored; and (2) that mineralization of this pool can be described by first order kinetics. Given these assumptions, the amount of N mineralized (N_m, mg kg^{-1}) at a given time (t, days), can be calculated from the expression,

$$N_m = PMN\ [1-\exp(-kt)] \qquad (4\text{-}1)$$

where PMN (mg kg^{-1}) is the amount of potentially mineralizable N corresponding to the N pool in the first assumption, and k (day^{-1}) is a rate constant. Potentially mineralizable N is viewed as the amount of N that could potentially be made available to plants by mineralization. Values of PMN and k can be estimated by fitting Eq. 4-1 to measured values of N_m.

Stanford and coworkers (Stanford et al., 1973; Stanford and Epstein, 1974) went on to experimentally determine the functional relationship between k and temperature and between k and soil-water content. This makes it possible to calculate amounts of N mineralized under field conditions when fluctuations in temperature and soil-water content are known.

Alternative Models. Although Stanford and Smith's (1972) approach has been used widely, several authors (e.g., Molina

et al., 1980; Juma and Paul, 1981; van Veen and Frissel, 1981; Deans et al., 1986) have proposed that more than one pool of soil organic N may be directly mineralized and should be explicitly considered in N mineralization models. Transfer from each of these pools is commonly described with first-order kinetics (Tanji, 1982).

In general, the multiple N-pool approach can be described mathematically as follows:

$$N_m = \Sigma N_{oi} [1-\exp(k_i t)]; \quad i=1,2,...,n \qquad (4\text{-}2)$$

where the subscript i represents the specific N pool, n is the total number of pools, N_{oi} is the amount of N (mg kg^{-1}) in the i-th pool at t=0, and k_i is the rate constant (day^{-1}) for the ith pool. Note that the total mineralizable organic N (equivalent to PMN) is equal to ΣN_{oi}. The simplest example of this approach is when n=2, as proposed by Nuske and Richter (1981). They described the two pools as "fresh" and "old" organic matter.

Another approach used to describe net mineralization is with zero-order kinetics (Tabatbai and Al-Khafaji, 1980; Addiscott, 1983). This model can be described mathematically as:

$$N_m = Kt \qquad (4\text{-}3)$$

where K (mg kg^{-1} day^{-1}) is a zero-order rate constant. With this approach, no assumption is made as to the number of N pools mineralizing. The implication is that the N pool(s) is (are) sufficiently large that they are not significantly

All of the above equations have been used to describe net N mineralization in laboratory incubation studies. For reasons that will be discussed in another section, a slight modification of Eq. 4-3 is presented in this chapter. The modification proposed is that a relatively small pool of highly mineralizable N, which is considered to be the result of experimental conditions, is included. This pool is assumed to mineralize by first-order kinetics, so that

$$N_m = A[1-\exp(k_f t)] + Kt \qquad (4\text{-}4)$$

with A (mg kg^{-1}) and k_f representing the amount of N in that pool at the initiation of the incubation and the rate constant (day^{-1}), respectively, and other terms are as defined previously.

The mineralization models above are summarized in Table 4-1. In subsequent discussion they will be referred to as the FO model for the first-order kinetic model; DFO for the two-pool first-order kinetic model; ZO for the zero-order kinetic model; and FOZ for the combined first-order, zero-order kinetic model.

Table 4-1. Summary of Models of N Mineralization Discussed.

Eq.#	Model	# N Pools	Reference	Equation
1	FO	1	Stanford and Smith (1972)	$N_m = PNM\ [1-\exp(kt)]$
2	DFO	2	Nuske and Richter (1981)	$N_m = N_{o1}\ [1-\exp(k_1 t)] + N_{02}\ [1-\exp(k_2 t)]$
3	ZO	1	Tabatabai and Al-Khafaji (1980)	$N_m = Kt$
4	FOZ	2	this study	$N_m = A\ [1-\exp(k_f t)] + Kt$

Objectives

Although the approach of Stanford and Smith (1972), as described above, has much to recommend it, several questions concerning its applicability to various situations have arisen. These questions include both matters of methodology and of data analysis.

One unfortunate aspect of the method is that a long (20 to 30 week) incubation period is required. This time can be shortened considerably if the rate constant k is known. In this context the assertion of Stanford and Smith (1972) and others (Oyanedel and Rodriguez, 1977; Campbell et al., 1981) that a "universal" k (k^*) can be used to describe all soils is particularly important.

Many Costa Rican soils are derived from volcanic ash and contain varying amounts of allophane. The effects of allophane are particularly evident in the Birrisito soil, which is known to contain significant amounts of allophane (Andriesse and Muller, 1973). Soil organic matter combines with allophane and thereby may be "protected" from microbial attack (Paul, 1984). This is consistent with the exceptionally high carbon content in that soil (Table 4-2). This may result in distinctive kinetics of mineralization and therefore require use of different k values.

Table 4-2. Selected soil properties.

Series+	Classif-ication	#	Crop*	%N	%OC	C/N	pH
B	TDa.		SC (>25 yrs.)	0.754	8.53	11.32	5.70
C	TDa.		CF (>15 yrs.)	0.437	4.48	9.88	4.33
I(P)	TDp.		M,M-B (7yrs.)	0.295	3.28	11.11	4.83
I(A)	TDp.		C-L-P (7yrs.)	0.284	2.95	10.40	5.16

+B, Birrisito series; C, Colorado series; I(P) Instituto series with perennial crops; I(A), Instituto with annual crops.
#TDa is Typic dystrandept, and TDp is Typic Dystropept.
*SC, sugarcane; CF, coffee; M, maize; M-B, maize+beans. C-L-P, cacao-Laurel-Plantain.

The method described above for estimation of N mineralization has been extended to mineralization of other nutrients (Tabatabai and Al-Khafaji, 1980; Maynard et al., 1983). Such extension requires some alteration in the methods originally proposed by Stanford and Smith (1972) because nutrients present in the leaching solution they used may be the object of study. If it is true, as has been claimed (van Veen and Frissel, 1981), that the availability of C and N as substrate limit mineralization rates, then the absence of those nutrients in the leaching solution should not effect N mineralization rates. In this case, the simultaneous study of the mineralization of several elements would be facilitated because a single soil sample (plus replicates) could be used to measure the mineralization of all elements of interest.

In addition, it was felt that the practice of air-drying samples prior to incubation, as recommended by Stanford and Smith (1972), should be investigated. The main reason for this is that in both of the instances mentioned above in which the zero-order kinetic model was used, field-

moist, rather than air-dried, soil was used. There were other differences in methodology but is seems likely that the kinetics of mineralization during incubation are influenced by the pretreatment used.

Although the first-order kinetic model has been used widely, the agreement between that model and measured data is seldom evaluated quantitatively. There have, however, been several claims that some alternative models are more appropriate.

With these considerations in mind, this study was designed to answer the following four questions: (1) Does the addition of nutrients following the leaching solution affect mineralization rates? (2) Does air-drying prior to incubation alter the kinetics of N mineralization? (3) Can k^* be used to describe N mineralization in soil influenced by volcanic ash?, and (4) Do the alternative models discussed better describe N mineralization? Answering these questions should lead to a better evaluation of the applicability of incubation procedures for estimating N mineralization in the field.

Materials and Methods

Soils

Four Costa Rican soils, representing 3 different soil series, were used for this study (see Table 4-2). The Instituto and Colorado soils were collected at CATIE located near Turrialba and the Birrisito soil was collected near the

town of Juan Vinas about 20 km away. Classification, cropping history and selected chemical properties of each soil are given in Table 4-2. Several bucket auger fulls of soil taken from a depth of 0 to 15 cm were composited. The two samples of Instituto soil were taken from adjacent plots with different cropping histories. Soil samples were frozen shortly after collection for storage (approximately 5 months).

Incubation Procedure

Soil samples were thawed at room temperature, sieved, thoroughly mixed, and divided into two roughly equal portions. One portion was spread over a laboratory bench and allowed to dry for two weeks. The other portion was further subdivided into two groups; one to be leached with 0.01 M $CaCl_2$ (M treatment) only, the other (P treatment) to be leached with a combination of the same solution and a -N nutrient solution as described by Stanford and Smith (1972). Three subsamples weighing approximately 30 g (oven-dry basis) of each group and from each soil were then placed in 0.2 µm Nalgene filter units (Nalge Catalog Number 120-0020), leached, and placed in an incubator maintained at 35 $\pm$ 1° C and 98 to 99% relative humidity. After two weeks the air dried soil samples were treated in the same manner.

The leaching procedure was as follows:

1. Place soils under a tension of 50 kPa using an apparatus similar to that described by MacKay and Carefoot (1981),

2. Add three 25 ml increments of 0.01M $CaCl_2$,

3. Place samples under 35 kPa tension,

4. Add 20 ml of 0.01M $CaCl_2$ to M treatment or 20 ml of -N nutrient solution to the P treatment,

5. Maintain tension until more than 90 ml leachate had accumulated (3 to 4 hours),

6. Place samples under tension of 35 kPa in incubator over night,

7. Collect remaining leachate the next day,

8. Bring leachate samples to volume,

9. Close off filter units, and,

10. Place in incubator.

This procedure was performed approximately 2, 4, 7, 10, 14, 18, 22, 26, and 30 weeks after the start of the experiment. The weight of each sample was recorded biweekly and evaporation loss was not permitted to exceed 0.5 g (1%). In general, soil weights were constant within 1 g during the course of incubation; however, in some cases the filter membrane lost its integrity and subsequent samples were lost. Air was circulated through each sample at least once a week during the incubation period.

Chemical Analysis

Total soil N was determined using a semi-micro Kjeldahl procedure (Bremner, 1965b). Total N in leachate was measured using reduced iron with steam distillation (Nelson and Sommers, 1975). Steam distillation with MgO and Devarda's alloy (Bremner, 1965a) was used for inorganic N

determination. Total organic C was measured from CO_2 evolution after oxidation using a Leco (Model Number 572-100) carbon analyzer. Soil pH measurements were made in a 1:2 soil:water paste. All soil analyses were performed in triplicate. All references to soil weight are on the oven-dry (105° C) weight basis.

Statistical Analysis

Analysis of variance of total cumulative N_m was performed using Statistical Analysis System (SAS) general linear models procedure (SAS, 1983). The experimental design was a split-split-plot with soil as the main plot, drying pretreatment as the subplot, and nutrient level the sub-subplot.

Goodness-of-fit was analyzed using the nonlinear regression procedure, NLIN (SAS, 1983), with the Marquad technique.

Results

Cumulative N Mineralization

Figures 4-1 through 4-6 show the net cumulative N mineralized over the 210 day incubation period for each soil and treatment combination. The curves in these figures are coded by three letters. Note that the first letter indicates the soil, or in the case of the Instituto series, the cropping history. The letter B represents Birrisito soil series; C denotes Colorado soil series; P stands for Instituto soil series with perennial crops; and A represents

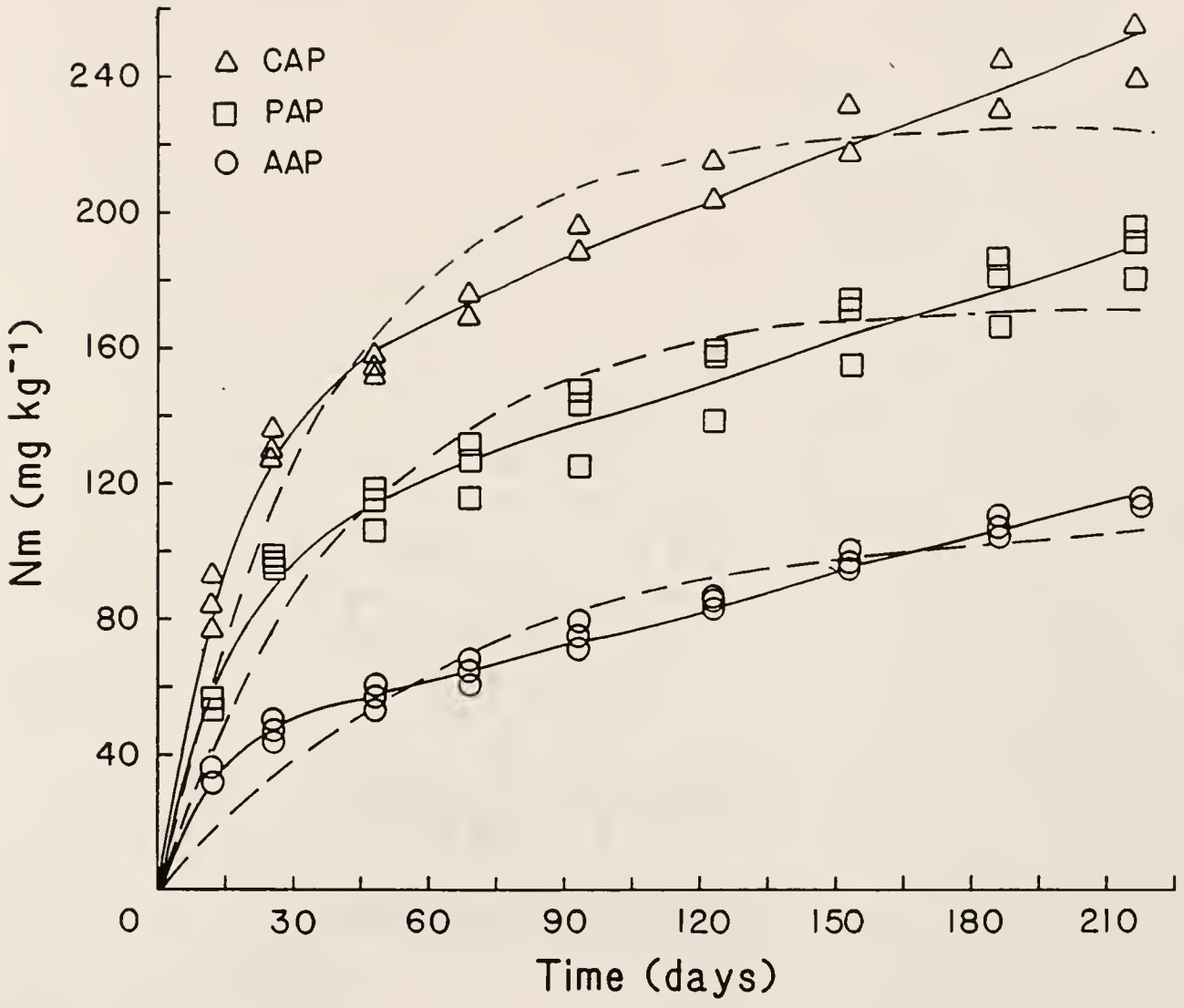

Figure 4-1. Cumulative net N mineralized with time for three soils receiving the air-drying and plus nutrient solution treatments. The FO and FOZ model best fits are indicated by the dashed and solid lines, respectively.

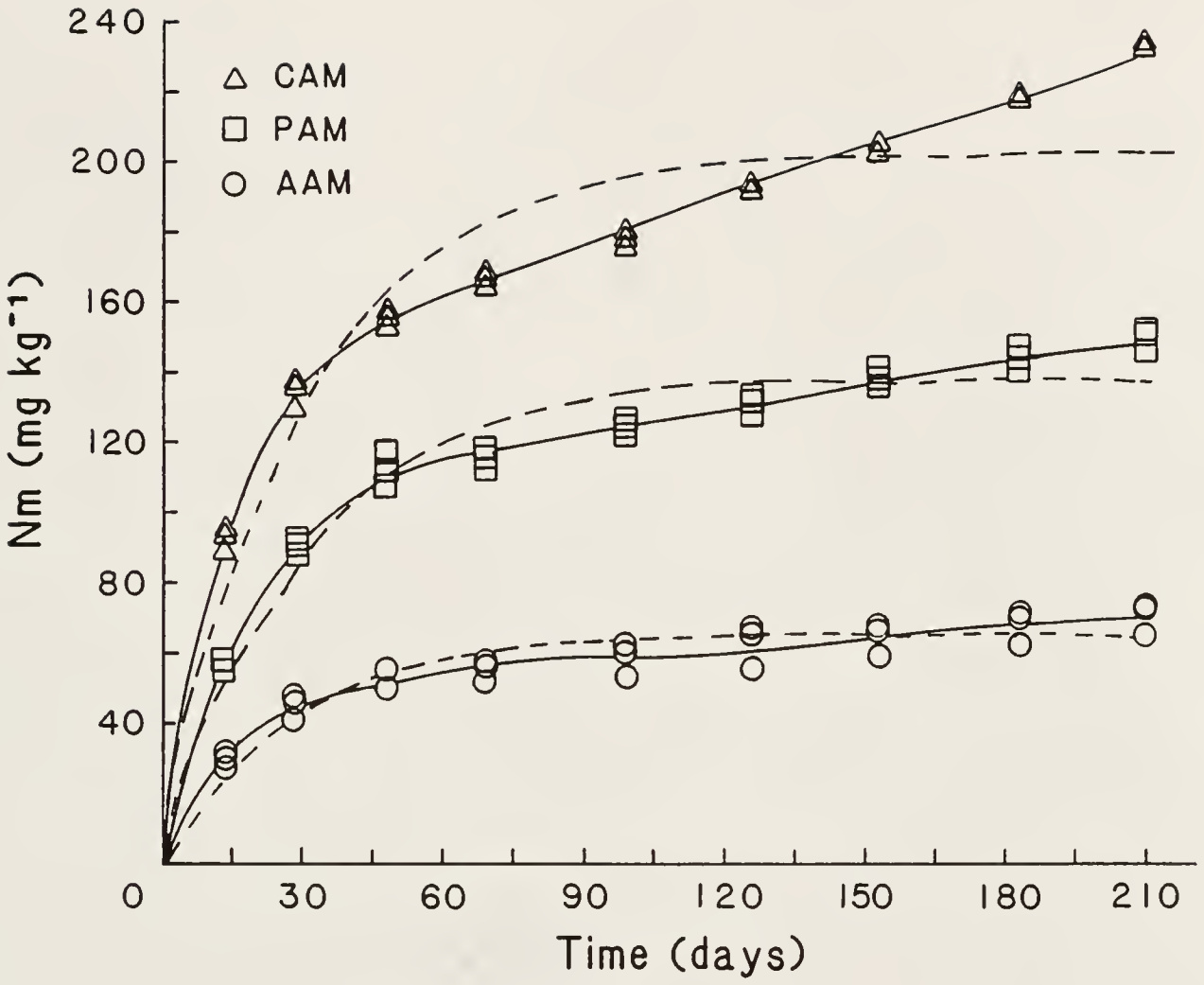

Figure 4-2. Cumulative net N mineralized with time for three soils receiving the air-drying and minus nutrient treatments. The FO and FOZ models are indicated by the dashed and solid lines, respectively.

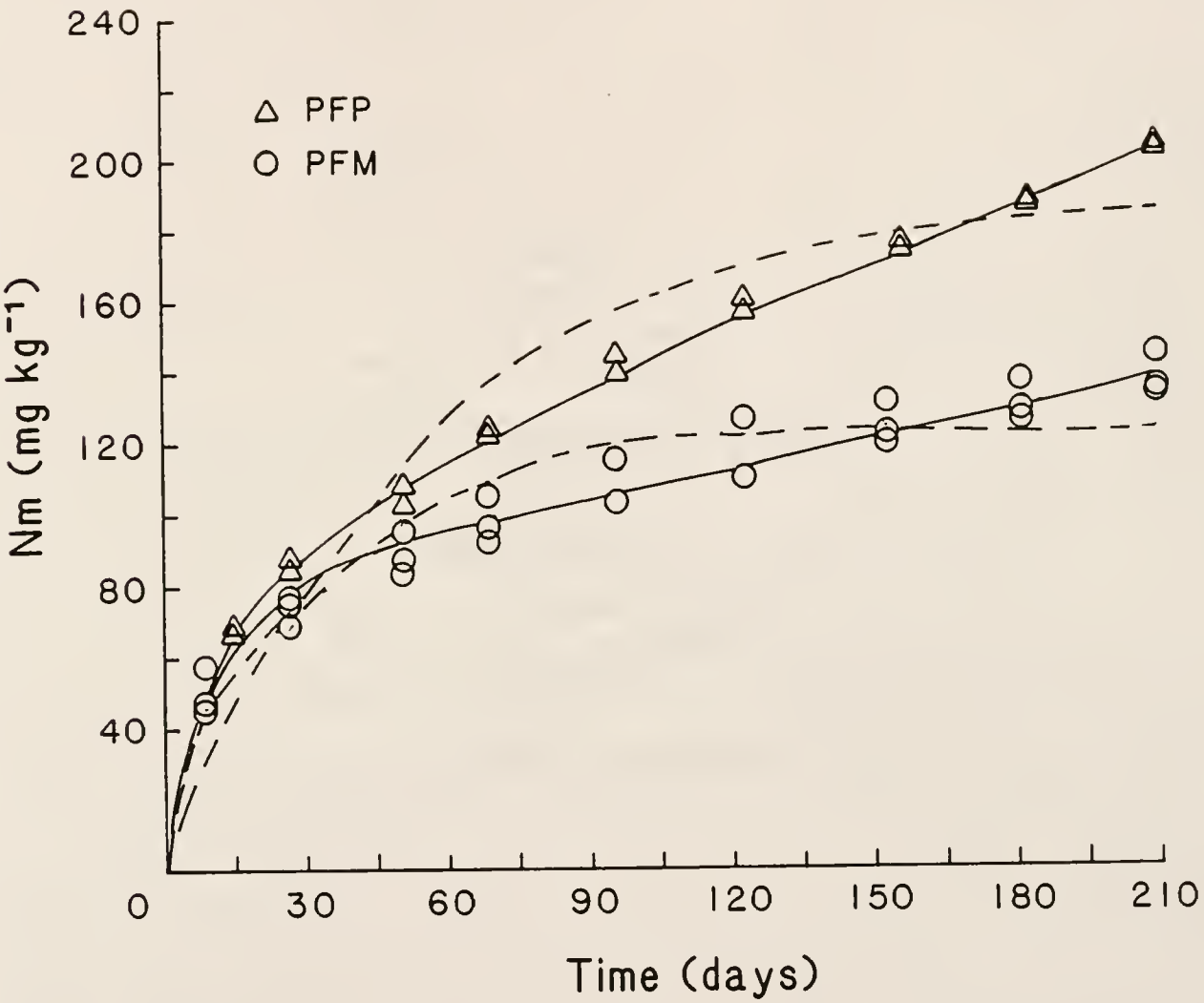

Figure 4-3. Cumulative net N mineralized with time as affected by nutrient solution treatment, with soil and drying treatment constant. The FO and FOZ model best fits are indicated by the dashed and solid lines, respectively.

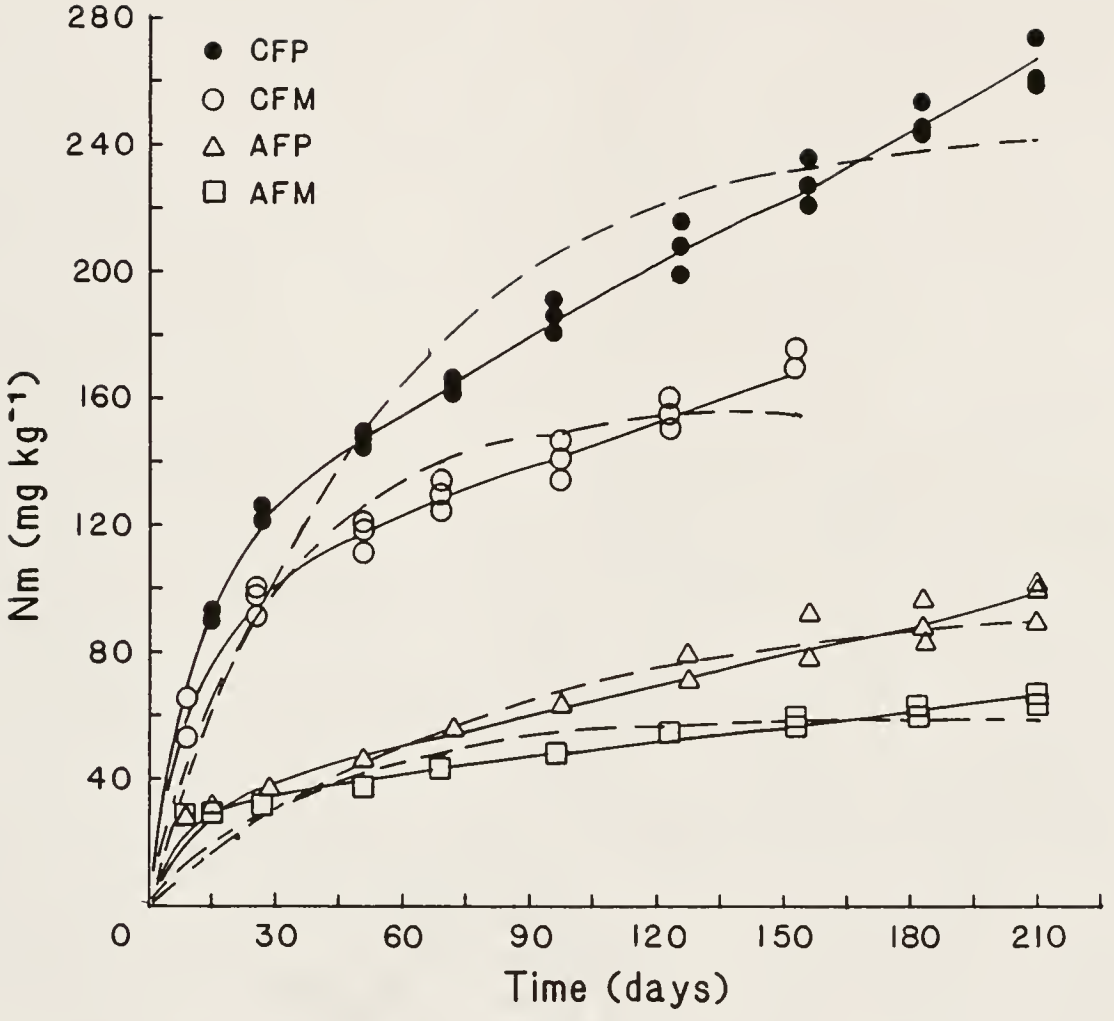

Figure 4-4. Cumulative net N mineralized with time as affected by soil solution treatment. The FO and FOZ model best fits are indicated by the dashed and solid lines, respectively.

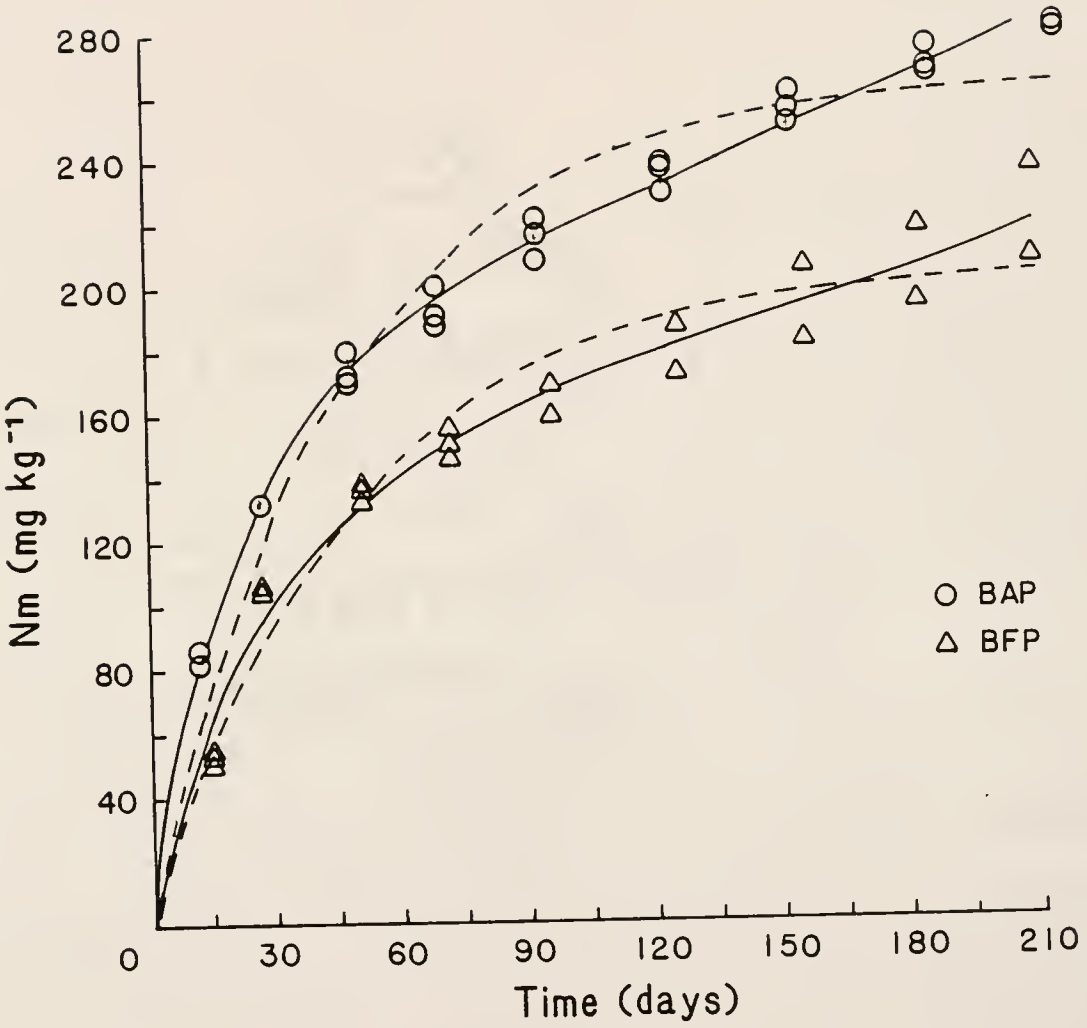

Figure 4-5. Cumulative net N mineralized with time as affected by air-drying treatment. The FO and FOZ model best fits are indicated by the dashed and solid lines, respectively.

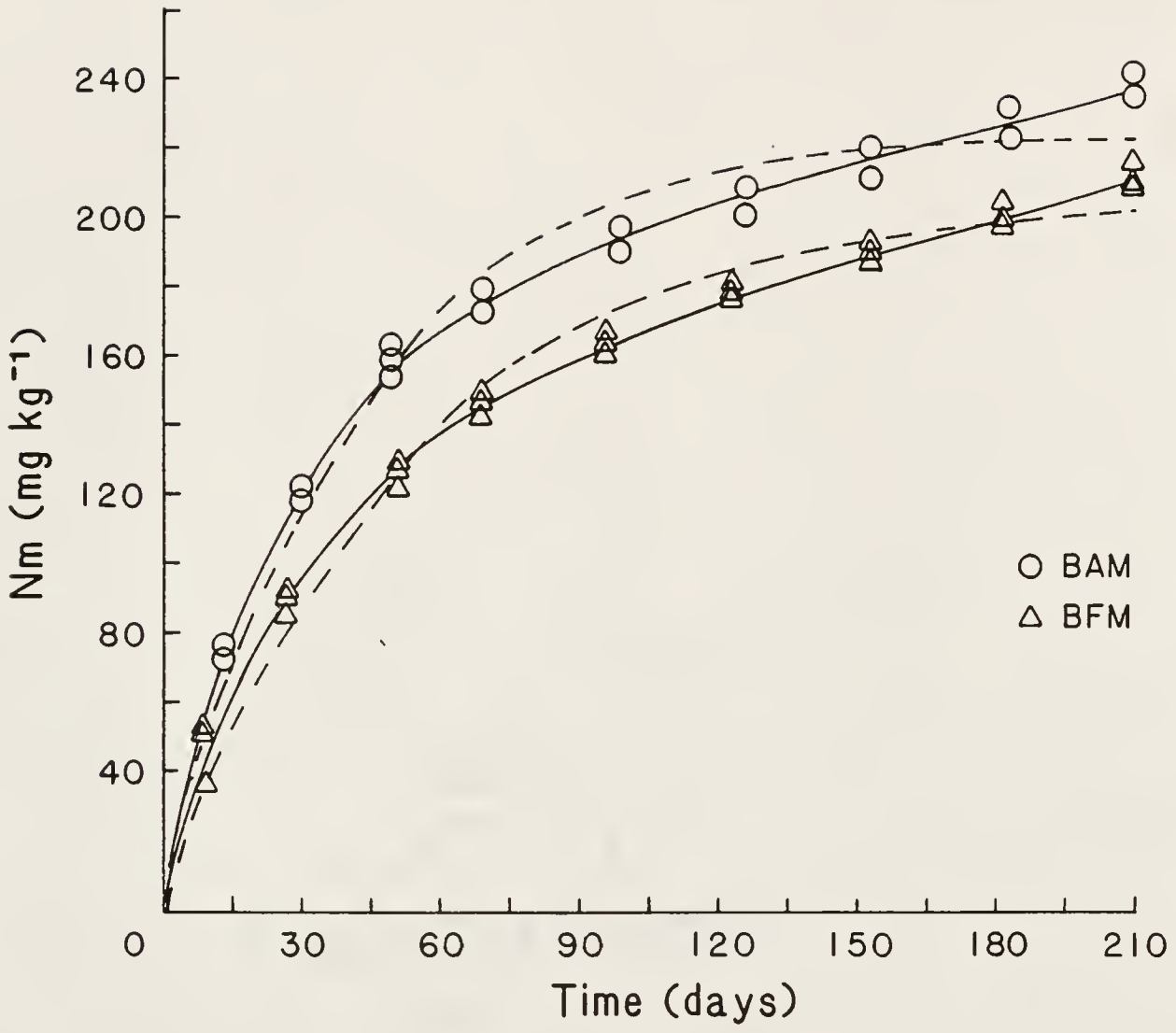

Figure 4-6. Cumulative net N mineralized with time as affected by nutrient solution treatment. The FO and FOZ model best fits are indicated by the dashed and solid lines, respectively.

Instituto soil with annual crops. The second letter refers to the pretreatment, either air-dried (A) or field moist (F). The third letter refers to the nutrient solution treatment with P for the plus nutrient solution (no N) treatment and M for the minus nutrient solution treatment. For example, the curve labeled BAP refers to Birrisito soil that was air-dried prior to incubation and given nutrient solution with leaching. The best nonlinear least sum of squares fit of two of the models described above, FO and FOZ, are represented by dashed and solid lines, respectively.

During the course of incubation, 8 of the 48 filter units failed to maintain tension due to decomposition of the cellulose filter membrane. This produced anomalous results and forced their omission. All three of the filter units in the CFM treatment failed after 150 days, hence the shortened curve.

Only measured inorganic N (the sum of NO_3^- and NH_4^+) are reported. Total N (the sum of inorganic and organic N) was measured in the first five extractions. Although there was significantly more total than inorganic N (α=0.95), inorganic N comprised 96% of that total. The difference between the two measures was not considered sufficient to warrant further measurement and the practice was discontinued. With the exception of the first extraction, virtually all of the inorganic N was NO_3^-.

Treatment Effects

This analysis was designed as a model-independent test of the statistical significance of the effects of soils and treatments on cumulative net N mineralization (N_m) under the described experimental conditions. At 210 days, N_m for each soil and treatment combination was analyzed as described in the previous section. In the case of the soil-treatment combination CFM, N_m and the associated standard deviation were extrapolated from the last available measurement (after 150 days).

The effects of all three variables were significant (α=0.95). In general, N_m values were in the following order: B≈C>P>A (Figs. 4-1,2,5,6). Both air-drying and addition of nutrient solution corresponded to significantly higher N_m values.

Analysis of variance performed for over the incubation perioid showed that both air-drying and nutrient addition effects were significant (α=0.95) for each extraction. The magnitude of the two effects, however, was quite different over the incubation period. The differences between average air-drying and field-moist values (A-F), and between average nutrient addition and omission (P-M) values over time are plotted in Fig. 4-7. The magnitude of the effect of air-drying was maximal after 30 to 45 days and then remained relatively constant, while the magnitude of the nutrient addition effect increased steadily after about 45 days.

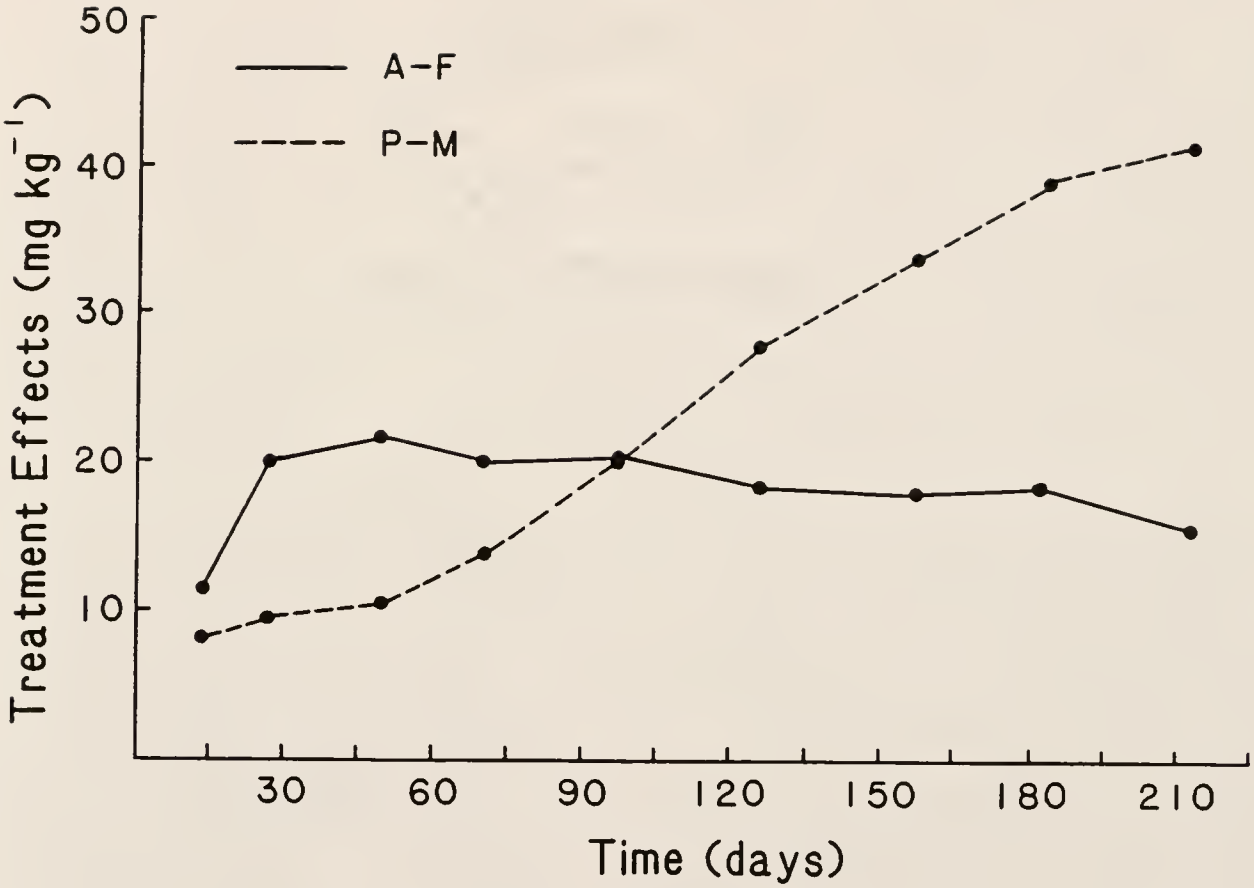

Figure 4-7. The effects of air-drying and nutrient addition over time as indicated by the difference between average air-dried and field-moist treatments (A-F), and by the difference between the average plus-nutrient and minus-nutrient solution (P-M) treatments.

These effects are evident in comparisons of the long, nearly portions of the curves in Figs. 4-1 through 4-6 after 30 to 45 days of incubation. Those segments in Figs. 4-3 and 4-4, in which P and M vary, can be seen to diverge with time. In contrast, a similar comparison in Figs. 4-5 and 4-6, where A and M are compared, shows nearly parallel increases in N_m after an initial separation.

Model Performance

The models described above will be discussed in the following terms: visual (qualitative) agreement between best fit curves and measured data, comparison of the total sum of squares, the frequency with which calculated curves intersect the 90% confidence interval associated with measured N_m, and the error associated with estimated parameter values. Parameter values associated with each model are summarized in Table 4-3.

Table 4-3. Model parameter values.

Soil Trt.	Model								
	FO		DFO				FOZ		
	PMN	k	N_{01}	k_1	N_{02}	k_2	A	k_f	K
	mg kg^{-1}	day^{-1}	mg kg^{-1}	day^{-1}	mg kg^{-1}	day^{-1}	mg kg^{-1}	day^{-1}	mg kg^{-1} day^{-1}
BAP	264	0.022	127	0.067	232	0.0050	162	0.051	0.569
BFP	205	0.206	126	0.040	881	0.0005	128	0.039	0.425
BAM	224	0.025	158	0.040	618	0.0006	160	0.040	0.367
BFM	205	0.019	98	0.048	183	0.0046	126	0.038	0.415
CAP	226	0.027	115	0.087	197	0.0052	140	0.067	0.519
CFP	247	0.019	105	0.096	600	0.0015	113	0.085	0.736
CAM	204	0.033	135	0.076	2069	0.0002	135	0.076	0.456
CFM	156	0.033	93	0.087	1318	0.0004	94	0.086	0.496
PAP	174	0.022	89	0.074	244	0.0024	99	0.065	0.425
PFP	189	0.018	64	0.127	265	0.0035	81	0.083	0.569
PAM	139	0.034	106	0.055	2404	0.0009	106	0.055	0.205
PFM	124	0.032	76	0.099	3343	0.0010	78	0.095	0.293
AAP	113	0.014	37	0.128	264	0.0017	41	0.105	0.353
AFP	97	0.126	29	0.114	412	0.0009	31	0.099	0.318
AAM	65	0.037	49	0.065	287	0.0004	49	0.065	0.104
AFM	60	0.024	25	0.201	60	0.0052	31	0.129	0.168

The total sum of squares is a measure of the goodness-of-fit between calculated and measured values. The average sum of squares of all 16 incubation curves for each of the 3 models is presented in Table 4-4.

Table 4-4. Indices of model goodness-of-fit.

	Model		
	FO	DFO	FOZ
% intersection*	50.0	97.9	94.4
Ave. Sum of Sq.	161.1	25.8	26.4

*calculated as the percent of 90% condence intervals about measured values intersected by calculated curves.

The confidence interval (α=0.90) was calculated for each individual extraction (there were 3 replicates). When calculated values for N_m fall within the confidence interval about measured values, the model calculation at the point is considered to represent the measurement relative to the precision of measurement. The proportion of calculated values falling within the confidence intervals, expressed as a percent, are also shown for each model in Table 4-4.

The precision with which parameter values were estimated using the curve-fitting procedure described was described by the relative error associated with those estimates (Table 4-5). The relative error was calculated from the average standard deviation for all 16 curves, divided by the mean for that estimate.

Table 4-5. Relative error of parameter estimations.

Model					
FO		DFO		FOZ	
Parameter	RE*	Parameter	RE	Parameter	RE
N_o	0.03	No_1	12.8	A	0.4
k^o	0.10	k_1	20.2	k_f	11
		N_{o2}	719	K	7
		k_2	753		

*Relative error, RE, calculated as the average standard deviation divided by the mean estimate.

FO model

Comparison of the dashed lines in Figs. 4-1 through 4-6 with the data reveals a systematic difference between the trend of the data and the fitted curves. In every case, the fitted curve is lower than the measured data at the beginning and ending of the incubation period, and greater at intermediate times. These trends are more clearly evident in soils with high final N_m values.

Computed values of the two critical parameters in the FO model are shown in Table 4-3. Values of PMN fall within the range of those found by Stanford and Smith (1972) and closely follow the trends of total N_m discussed previously. Values of k, however, which range from 0.0126 to 0.0373 (day^{-1}) clearly are not close to 0.0077, which was proposed by Stanford and Smith (1972) as the k^* value. In all cases, estimated k values were significantly greater (α=95%) than 0.0077 day^{-1}. In addition, there was little internal consistency among those estimates, the largest k value being about 3 times greater than the smallest.

The goodness-of-fit, as indicated by the sum of squares and percent intersection of estimated confidence intervals (Table 4-4) indicates that, on both grounds, the fit is relatively poor with the FO model. However, the error with which the parameters are estimated is relatively low (Table 4-5).

DFO model

Plots of the DFO model are not included because they were virtually indistinguishable from those of FOZ model. The improvement in fit is evident from the greatly reduced sum of squares and greatly increased percent intersection of confidence intervals (Table 4-4). The relative errors associated with the parameters used to obtain these improved fits, are however, quite high (Table 4-5). Estimates of N_{02} and k_2 are especially poor.

FOZ model

Visual examination of the solid lines in Figs. 4-1 through 4-6 indicates excellent agreement between calculated and measured values throughout the incubation period. This is reflected in the calculated goodness-of-fit parameters shown in Table 4-4. In both these respects DFO and FOZ models are very similar. The error associated with estimated parameter values is, however, quite different in the two models (Table 4-5). In this respect the FOZ model is intermediate between the other two models.

Discussion

Treatment Effects

Significantly more N was mineralized in those samples that were air-dried. Numerous studies have shown that air-drying causes solubilization of highly decomposable nitrogenous compounds (Stevenson, 1956; Powlson and Jenkinson, 1976; Bartlett and James, 1980). This results in a flush of N mineralization (a relatively high net mineralization rate) followed by slower rates similar to those of soils that had not been air-dried (Williams, 1967; Nordmeyer and Richter, 1985). The same pattern was observed in this study.

The size of this flush is dependent on the severity of the treatment (e.g., temperature and length of time) and the soil used (Soulides and Allison, 1961; Marumoto et al., 1982b). It is postulated that the solubilization of organic compounds observed after air-drying is either the result of physical disruption of organic matter structure or due to the death of part of the microbial population, whose biomass is then rapidly mineralized. Using ^{15}N isotope techniques, Marumoto et al. (1982a) found that about 76% of the flush was from the microbial biomass, thus demonstrating the feasibility of the second explanation.

The anticipated fit of the F treatment to the ZO model was not observed. There was, however, one major difference between the procedure used by earlier investigators and that used in the present study. In this study, all soils were

frozen prior to incubation. Effects of freezing similar to those ascribed to air-drying have been documented with the same explanations offered (Jenkinson and Powlson, 1976). These effects are generally considered to be slight relative to the effects of air-drying (Bartlett and James, 1980). However, it is reasonable to expect that the soil microflora in tropical regions would be more sensitive to freezing than the soil microflora in temperate regions, where these studies have been conducted. The effects of air-drying and freezing can be added to a longer list of pretreatment effects that can be expected to produce a flush of N mineralization (Jenkinson and Powlson, 1976; Nordmeyer and Richter, 1985).

The effect of nutrient addition was also statistically significant. This indicates that the microbial populations that mineralize N suffered nutrient deficiencies under the experimental conditions. Thus, C and N are not necessarily limiting factors in mineralization. It should be noted, however, that the comparison made here is between relatively high nutrient inputs and extremely high leaching rates under conditions of near optimal temperature and soil-water so that the maximum effect is expected. The initial similarity between P and M nutrient treatments may be due to nutrients in the organic matter made soluble by the pretreatment.

Model Performance

FO model

Two major discrepancies between the measured incubation curves and the FO model were noted in the previous section: k values measured were significantly different from the "universal" k; and there were systematic differences between fitted and measured curves. These discrepancies are not unique to this study although they have frequently escaped notice and comment by earlier workers. Two reasons for this are: the curve fitting methods used to obtain k and PMN values; and the manner in which results are often presented.

The method of curve-fitting employed by Stanford and Smith (1972) uses linear regression of log-transformed data to estimate k values. Smith et al. (1980) and Talpaz et al. (1981) have argued that a different approach, using nonlinear regression of untransformed data (NLIN), is more appropriate on theoretical grounds. They also showed that the NLIN method resulted in improved (in terms of sum of squares) fit of curves to data. Talpaz et al. (1981) showed that use of NLIN techniques tends to produce higher, more variable, k values, which is a result also found by Broadbent (1986). This difference is due to the relatively greater weight given to larger values of N_m when the log-transformed data are used.

Examples of both procedures can be found in the literature. Although the k values obtained in this study are considerably higher than those of Stanford and Smith (1972),

they fall well within the range found by workers using the NLIN procedure (Smith et al, 1980; El-Harris et al., 1983).

Data in the literature are generally reported in two forms; as cumulative net mineralization versus time or versus $t^{1/2}$. Visual inspection of most of these curves (e.g., Fiegin et al., 1974; Mary and Remy, 1979; El-Harris et al., 1983; Hadas et al., 1986) shows a qualitative similarity with those in Figs. 4-1 through 4-6. Those curves plotted against $t^{1/2}$ generally show a linear relationship (Stanford and Smith, 1972; Cassman and Munns, 1980). Figure 4-8 shows the best nonlinear least squares fit to two curves that are linear with $t^{1/2}$. The fit is good when the slope is small and much worse for greater slopes. Note that the systematic differences observed in both cases are similar to those shown in Figs. 4-1 through 4-6.

From these observation it may be concluded that the discrepancies observed in this study are common to many others. It appears that the course of mineralization on these tropical soils of differing mineralogy is qualitatively similar to other soils studied. It also appears that the applicability of the FO model deserves closer inspection.

The FO model predicts that, with time, the PMN will be completely mineralized. If that pool is the only source of N then accumulation of N_m should cease after that time. This cessation was not observed in this study. In fact, even when incubations have been carried for 50 weeks it is

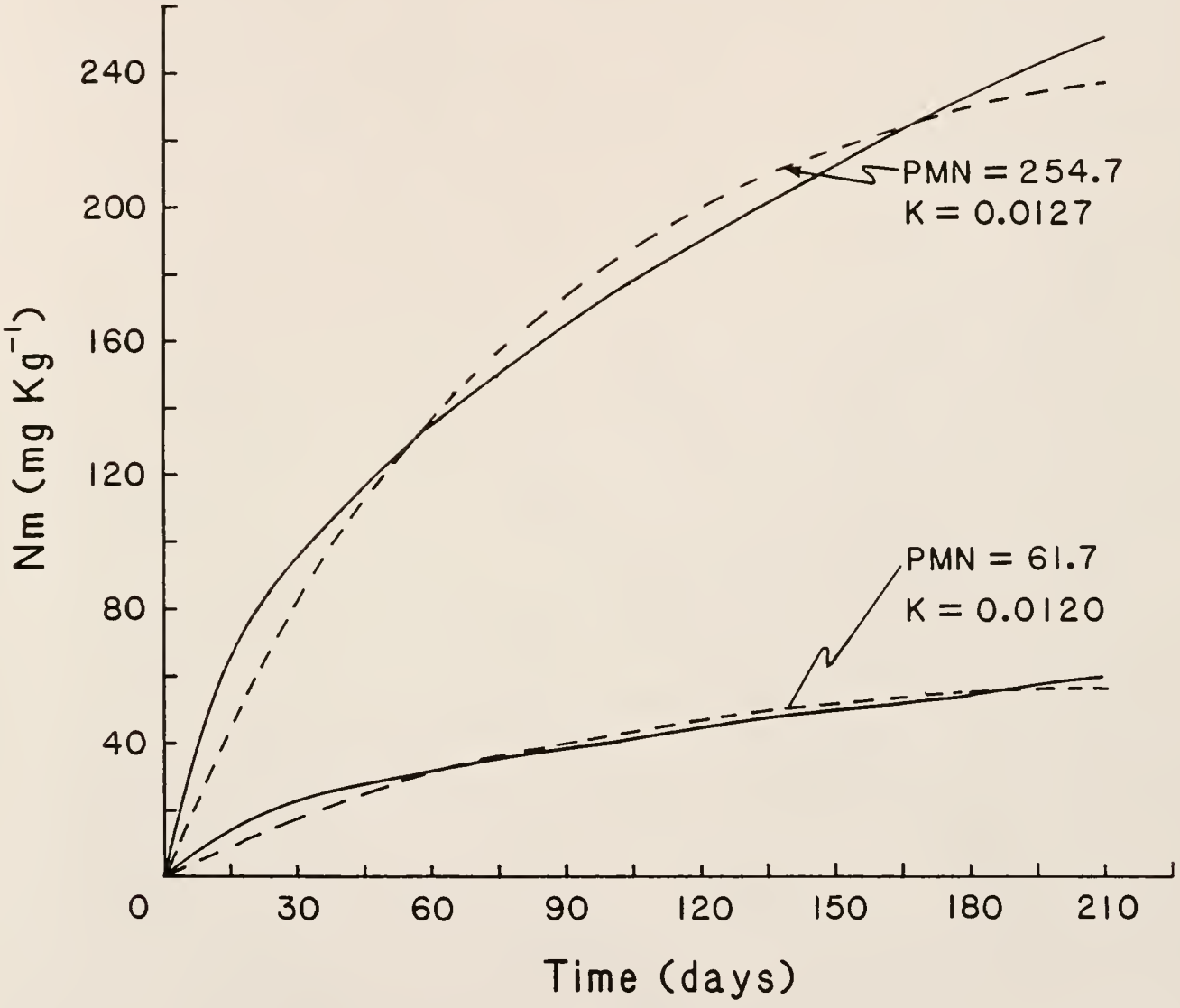

Figure 4-8. Best nonlinear least squares fit of the FO model (dashed line) to two curves that are linear with respect to the square root of time.

not observed (Stark and Clapp, 1980). This suggests either that the mineralization of PMN does not follow first order kinetics or that more than one pool of N supplies the N that is mineralized.

It is evident from the effects of air-drying observed in this study and the effects of other pretreatments in general, that part of the N mineralized in most incubation studies can be attributed to pretreatment effects. It has also been noted that, in the absence of pretreatment, there is significant N mineralization. Therefore, at least two pools of N must be considered to contribute to N mineralization.

Application of the FO model to field conditions introduces more problems. According to the FO model, the amount of N residing in the PMN pool should decrease as soil organic N is mineralized during the cropping season. In fact, PMN has been measured during the course of a cropping season in two recent studies (El-Harris et al., 1983; Nordmeyer and Richter, 1985). One study found no discernible trend over time (Nordmeyer and Richter, 1985), and the other found PMN to increase with time (El-Harris et al., 1983). These findings suggest that the effects likely increases in the microbial population during the cropping season are at least partially countered by any diminution of the "available" N.

DFO model

Additional pools of N have been represented in models as mineralizing by first-order kinetics (e.g., Nuske and Richter, 1981, Deans et al., 1986). The number of pools considered is variable. From the above discussion it is clear that one pool to account for pretreatment effects must be considered. A second pool may be considered as a composite of all other organic N, or as a specific pool that mineralizes more rapidly than other organic matter.

Evidence that more than two pools contribute significant amounts of N has come from tracer studies (Paul and Juma, 1981). We did not consider additional pools for two reasons. First, the goodness-of-fit obtained using two pools was excellent and there could be little improvement made by adding terms. Thus, it was felt that the data were not sufficient to justify additional terms. Second, addition of pools would result in reduced precision with which parameters were estimated. Even with two pools the error associated with estimated parameters was very high (Table 4-5). These errors stem from the nature of the measured mineralization curves. That is, an exponential relationship for the second pool is fit to what must be assumed to be the very base (virtually linear portion) of the second curve. Using only this information it is possible to approximate measured results with a wide range of N_o and k combinations.

The basic problem here is that simple incubation studies, which have been designed to estimate N

availability, do not yield sufficient information to justify the construction of complex models. Such models should be capable of accurate description of the results from these studies, but the parameters used must come from additional experiments involving, for example, the use of ^{15}N (see Paul and Juma, 1981). If simple incubation studies are to be of value in estimating N availability, the parameters derived from them should be consistent with measured mineralization rates and the model used be sufficiently simple that parameters can be precisely estimated.

In this study, the parameter values determined for the DFO model resulted in estimates of N mineralization that were consistent with measurements, the the precision with which those parameters were estimated was relatively low (Table 4-5).

FOZ Model

The FOZ model, as described previously, also consists of two terms, a first order and a zero-order kinetic term. The first-order term is interpreted as representing the pool of N made mineralizable by pretreatment. The other term describes the net mineralization of all other soil organic N. When pretreatment effects are eliminated or are accounted for by preincubation, the first term drops out and the linear relationship that has been observed under such conditions (Tabatabai and Al-Khafaji, 1980; Addiscott, 1983) is predicted.

Analysis of variance performed on the parameters shows significant differences that are consistent with the interpretations given above (Table 4-6). Values of A, for example, are significantly greater for air-dried than field-moist soils, which is expected due to the increased severity of the former pretreatment. Values of K are significantly greater for samples receiving added nutrients than those not. This reflects the apparent stimulation of microbial activity that results from nutrient addition. The effect of soils on all parameters was significant, which is a reflection of differing soil properties and management.

Table 4-6. Summary of treatment effects.

Variable	Parameter		
	A	k_f	K
Soils	*	*	*
Dryness	* (A>F)	-	-
Nurient	-	-	* (P> M)

* significance at 95% level
- no sigificane at 95% level

The first order term dominates the N mineralization rates at small times (<30 day). It has been proposed (Ayanaba et al., 1976) that the magnitude of A, or a quantity analogous to it, is directly proportional to the size of the microbial population which, in turn, should be related to microbial activity and hence mineralization rates. Thus, the magnitude of A should serve as an index of soil organic N availability. This approach clearly demands standardization of pretreatment. Inspection of the data from this study show that there is a fairly strong correlation between

A and K. The weakness of this approach is that, at best, it provides an index of soil organic N availability.

After 30 to 45 days of incubation, a quasi-steady state was achieved in which net N mineralization between leachings was equal to N leached. This is described by the second, zero-order term in the FOZ model. The success of this term in describing the data implies that the rate of N mineralization is not limited by the amount of substrate during the incubation period. The substrate involved may be composed of smaller pools, but the implication is that these pools are sufficiently large relative to the amount of N mineralized that they do not become limiting. The term "conglomerate kinetics" was used by Addiscott (1983) to describe this situation. Differences in K values between soils may be attributed to differences in the relative sizes of N pools in the different soils.

The K value of a soil is considered to be a function of temperature, soil nutrient content and soil-water potential. Because it is related to large N pools it is expected to remain fairly constant over time. Incubation studies of soils over time have shown that, in general, N mineralization rates tend to stabilize at the same rate after long incubation times irrespective of sampling date (Nordmeyer and Richter, 1985), which supports that expectation.

K values may describe a "basal mineralization rate" which, in the short run is augmented or reduced by addition of exogenous organic N. In the long run, factors such as

the nature of crop planted and management practices are expected to influence K. This may explain the measured differences between P and A soils.

A number of other equations have been used to describe N mineralization during incubation (Juma et al., 1984; Broadbent, 1986). Some of those would undoubtedly produce excellent agreement between measured and calculated curves using relatively precisely estimated parameters. The advantage of the FOZ model is that it differentiates between pretreatment effects and N mineralization from other sources.

In terms of application to the field conditions encountered at the sites of this study (ie., humid tropical), it seems reasonable to focus on a rates of mineralization as opposed to a particular fraction of organic N (e.g., PMN). In such a climate the mineralization of N is relatively constant over the year, hence any given soil N fraction must be continuously depleted and renewed, and the rate of this renewal is what is of interest.

Conclusions

Addition of nutrients after leaching resulted in significantly increased net N mineralization rates. Thus, results from studies that use the same sample to measure mineralization of more than one element (with accompanying reduction in applied nutrients) cannot be directly compared to studies that follow the original procedure proposed by

Stanford and Smith (1972). The increase in net N mineralization rate was constant over the duration of the incubation period. It appears that microbial activity is stimulated by the more favorable environment induced by the greater availability of nutrients.

Air-drying samples prior to incubation resulted in a flush of mineralization for the first 30 to 45 days of the incubation period. It is likely that other pretreatments, freezing in particular, had qualitatively similar effects. Previous work indicates that the flush results from the solubilization of organic N compounds due to the death of the microbial population. This flush greatly influences the interpretation of measured cumulative N mineralized over time in incubation studies.

The "universal" k value, k^*, for the FO model is not appropriate for any of the soils or treatment combinations studied. This does not appear to be the result of any peculiar properties of the soils studied. Rather, it is a result of the method of analysis used to determine k values. In addition, it appears that the assumption that one N pool contributes to mineralization is not valid when common methods of pretreatment are used.

Both of the alternative models examined describe net N mineralization better than the FO model. The DFO model was shown to agree very well with measured net N mineralization, but the precision with which parameters were estimated was so poor that little confidence could be placed in them. The

FOZ model also described measured data very well, and the precision of parameter estimation was considerably better than for the DFO model. Other, more complex models could undoubtedly achieve excellent agreement, but, unless the required parameters were estimated independently, would suffer the same limitations as the DFO model.

The first-order kinetic term in the FOZ model describes the mineralization of N made mineralizable by pretreatment. If the nature of pretreatment is carefully controlled then the first term is probably indicative of the size of the microbial populations. The zero-order term is a basal mineralization rate. The successful application of the zero-order term indicates that the source of mineral N in these incubation studies was relatively large pool(s) of N.

CHAPTER V
OVERALL SUMMARY

Increased pressures for land use from a variety of sources make it important to develop sustainable, productive cropping systems in the humid tropics. One of the constraints to this is the potentially large nutrient leaching loss from agricultural fields in the region. It has been suggested that cropping systems with high species density, deep rooting habit, and continuous nutrient demand, should be more conservative in terms of applied nutrient use than annual, monocropped systems. In this study, we examined water movement, nutrient leaching and release by mineralization in to contrasting cropping systems to determine differences in nutrient use efficiency.

Water Movement and Nutrient Leaching

One of the main reasons that leaching has not been studied extensively in tropical regions is that such studies are difficult. There are no means currently available of measuring leaching directly. For this reason, leaching losses must be calculated from indirect measurements. This requires that assumptions be made concerning the nature of nutrient movement in the field.

The approach taken in this study was to calculate nutrient movement on the basis of water fluxes and solute concentrations. In order to apply this approach, the manner

in which water flows through the soil must be known. In particular, there was concern that flow might take place in localized channels (macropores) which would result in the effective bypassing of the soil matrix.

Tritiated water was displaced through "undisturbed" soil columns under a range of soil-water tensions to determine the nature of soil-water flow in soil at the experimental site. Although a high degree of dispersion was observed, significant bypassing was not observed under tensions other than at or very near 0 kPa (saturation). Comparison of field-measured saturated hydraulic conductivities with rainfall intensities indicated that such flow conditions are very rare. This is consistent with measured changes in the water table depth in response to rainfall events and the observation that ponding did not occur at the site. This led us to conclude that solute movement could be described with modeling approaches that assume that all soil-water participates in convective transport.

A field-scale, capacity-parameter based, model of water and solute movement was then developed that was conceptually based on the above findings. Solutes from a given input were assumed to be dispersed about a solute front that travels through the soil at the pore-water velocity, v_o. It was further assumed that soil-water drained to a consistent value, θ_{fc}, after rainfall events. Problems associated with the proximity of a water table were circumvented by using

the water table depth as an input and by not considering the upward movement of water explicitly.

Simulated soil profile water contents closely approximated those measured over the validation period of 96 days in both plots. Simulation was then extended to a longer, 260 day period that commenced 150 days prior to the validation time period. After 150 days of simulation, the agreement between measured and simulated profile soil-water contents was reasonably good. These results were a further confirmation that the basis of the model is sound.

Simulation results were used to calculate: (1) the net deep percolation to be used to estimate net nutrient leaching loss, and (2), the movement of a nonadsorped solute front through the soil profile.

The simulated net deep percolation was slightly greater from the monocropped annual (MA) plot than from the mixed perennial (MP) plot. The difference was due to the greater actual evapotranspiration (AET) from the MP plot. The measured soil solution concentrations of N, K^{+}, Ca^{2+}, and Mg^{2+} at 90 cm depth over the same time period were approximately constant over time and much grater in the MA plot than the MP plot. Estimation of net leaching loss (the product of soil solution concentration and net deep percolation) were consequently much greater from the MA than the MP plot.

The simulated movement of a nonadsorped solute front was somewhat faster in the MA plot than the MP plot. The

greater AET and Θ_{fc} in the MP plot account for this. The results indicate that succeeding crops in the MA plot do not receive much beneficial effect from fertilizer NO_3 (which is weakly adsorped) applied to previous crops.

The concept of nutrient residence time was introduced to characterize the sensitivity of the two cropping systems to leaching losses. The solute residence is considered to be the length of time a nonadsorped solute can be expected to reside within a given soil depth. It is based on the concepts used to calculate the movement of the solute front in the model with a sight modification to allow the use of average climatic data. Soil, crop, and climatic factors are accounted for with three parameters. The soil parameter is what was termed the leaching depth of the soil ($\Theta_{fc}D$), which is the amount of water required to displace a nonadsorped solute beyond the soil to the depth of interest when the initial soil-water content is Θ_{fc}. In this study only the movement of a nonadsorped solute was considered but the concept could be extended to adsorped solutes by calculating the leaching depth (LD) as

$$LD = \Theta_{fc}\ D\ RF, \qquad (5\text{-}1)$$

where RF, the retardation factor, was described in Chapter II.

The crop and climate parameters, AET and rainfall (TR), respectively, were combined into a single parameter, the cumulative effective rainfall (CER), which is simply AET -

TR. The solute residence time is then the length of time required for the CER to exceed the leaching volume.

Solute residence times calculated for the MP plot were about 1.4 times greater than those for the MA plot. Most of that difference was due to the somewhat greater Θ_{fc} at the MP plot. This result, which was somewhat surprising, can be explained in terms of both the AET and the TR. AET differences between the two systems were not as great as had been expected for two reasons: (1) there was considerable loss of water from the soil by evaporation and transpiration by weeds during the fallow periods, and (2) the transpiration from the MP plot was reduced during the dry season. These effects are enhanced by the fact that the TR in this climate is sufficiently greater than the AET that crop differences were obscured.

Mineralization and Nutrient Cycling

Aside from differences in water movement, differences in leaching losses from the two plots may be attributed to differences in the rate of release of nutrients from litter or crop residue and soil organic matter. This would effect the rate at which nutrients enter the soil solution and thereby effect the potential for leaching loss.

The laboratory incubation method of Stanford and Smith (1972) was investigated as a possible basis for for determining the rate of N mineralization from soil organic matter. The kinetics of mineralization measured did not follow those proposed by Stanford and Smith (1972). In

addition, the application of first-order kinetic N mineralization models to field conditions is questionable because they do not account for the addition of N to the potentially mineralizable N pool during the cropping season.

An alternative model, composed of two terms, one zero-order and the other first-order kinetic, was proposed. The first-order kinetic term was interpreted as describing the effects of sample pretreatment on mineralization rates. Results from the present study indicate that significantly more N was mineralized from soils that were air-dryed prior to incubation than those not. The zero-order term was interpreted as describing the "basal mineralization" rate that results from mineralization from large organic N pool(s).

The alternative model quite successful at describing cumulative net N mineralization during incubation. Either of the two terms used might be used to estimate soil N availability, but there are problems associated with both. The first-order kinetic term, which is probably related to the soil microbial biomass, could provide an index of the capacity of the soil to mineralize organic N. However, application requires knowledge of the relationship between microbial biomass and N mineralization rate, which can be expected to be dependent on numerous environmental conditions.

Application of the zero-order rate coefficient, K, would seem to be appropriate since it describes

mineralization rates in the absence of experimental artifacts. However, it too is certainly dependent on environmental conditions such as temperature, soil-water content, and nutrient availability. These limitations make even relative comparisons of parameter values questionable except where environmental conditions are essentially equivalent.

Overall Assessment of Cropping Systems

It is clear that the net loss of nutrients from the mixed perennial cropping system was much lower than from the monocropped annual cropping system. This statement can be based on the soil solution data alone. The reason for the observed difference is not so clear, however. At the outset of this work it was believed that differences in transpirational demand would be sufficiently great that the solute residence time would provide a reasonable explanation. However, for reasons discussed previously, the differences in solute residence time were not as pronounced as anticipated.

One explanation is simply that the mixed perennial system received less nutrient input. It is necessary to consider inputs from both fertilizer application and organic matter decomposition. While the fertilizer additions are known, this is not the case for organic additions. As an alternative to using information from incubation studies, the assumption can be made that the rate of nutrient entry from organic sources is equal to the rate of litter or crop residue addition. Eventually, at steady state, this must be

the case. The work of various authors (Jenny et al., 1949; Sanchez et al., 1982) indicates that approximate equilibrium in tropical regions is achieved relatively rapidly. According to those studies, the equilibration time of 6 to 7 years for the two cropping systems examined in this study is likely sufficient for such conditions to prevail.

Following this approach, the annual addition of (kg ha^{-1}) of N, K^+, Ca^{2+}, and Mg^{2+} to the mixed perennial plot of 95, 57, 108, and 43, respectively, measured by Alpizar et al. (1983), can be added to annual fertilizer additions. The resultant total addition is 235, 77, 108, and 43 kg ha^{-1} yr^{-1} of N, K^+, Ca^{2+}, and Mg^{2+}, respectively. It should be noted that the estimation of litter input is a considerable underestimation because inputs from pruning were omitted by Alpizar et al. (1983). Using residue inputs for maize provided by Sanchez (1976), the estimated total annual input of N and K^+ (estimates of Ca^{2+} and Mg^2 are questionable in this context) are 300 and 100 kg ha^{-1}, respectively. Viewed from this perspective, it does not appear that differences in nutrient input alone can explain the observed differences in soil solution concentration.

In my opinion, there are two reasonable explanations for the observed differences in cropping systems. The first, and probably more important, is the well developed rooting system in combination with nutrient demand, that exists throughout the year in the mixed perennial system. This means that any nutrient entering the soil solution must

travel through the entire rooting system before it is lost by leaching. In contrast, much of the fertilizer nutrient in the monocropped annual system is applied at planting, when there are no roots at depth. In addition, active roots are essentially eliminated from the profile at each harvest, rendering the recovery of nutrients located in the lower portions of the profile unlikely.

The other explanation is based on the effects of the litter layer in the mixed perennial system. The presence of carbonaceous material at the soil surface could result in temporary immobilization of NO_3^-. This NO_3^-, plus that released by mineralization of litter fall, is expected to enter the soil solution slowly, allowing the crops greater opportunity for absorption.

Future Work

As is often the case, the results from this study point to the kind of work that should be undertaken in the future. The basic approach to the study of cropping systems employed in this study was to to monitor the various cropping system properties (e.g., soil solution concentration and soil-water content) as they changed "naturally" over time. While this approach does provide considerable insight into the ranges of values and relative importance of processes that occur in the field, it does not provide detailed, quantitative information about those processes.

For example, considerable information concerning the nature of solute movement in the field could be obtained by

implementing smaller scale, intensively measured experiments in which tracers and water are applied at critical intensities. In addition, smaller scale, intensively measured subplots could be monitored intensively to better assess the movement of water through the soil and the response of the water table to rainfall inputs. By the same logic, a much clearer picture of the relative movement of applied N in both systems could be obtained by more intensive measurement of subplots.

On a slightly different level, the overall importance of various processes would be better understood if more care were taken to evaluate other components of the cropping systems. In this study, considerable effort was devoted to the evaluation of leaching losses, which were considered to be the "missing link" in many nutrient balance studies, at the expense of the rest of the chain. Probably the single most important set a data that were missing was the actual crop uptake of nutrients.

One conclusion from the N mineralization study was that laboratory incubations provide a questionable basis for the estimation of N mineralization under field conditions. This result is not surprising in light of the overall failure of any laboratory procedure to be widely accepted in spite of considerable efforts in development. This is not to say that further study into the mechanisms of N mineralization, possibly using incubation techniques, is unwarranted. On the contrary, such research is required if better

understanding and eventually better assessment of N mineralization is to be achieved. At present, however, it seems that reasonably good evaluation of organic inputs can be obtained simple mass balance considerations.

In general, it appears that there is considerable potential for the use of cropping system manipulation as a means of achieving high efficiency of applied nutrient uptake. It should be possible to isolate the mechanisms responsible. If this is done then we will have a rational basis for the design of future cropping systems.

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BIOGRAPHICAL SKETCH

Mark S. Seyfried was born in Santa Rosa, California in the year 1954. Most of his early years were spent in the near by town of Modesto. The easy access to both the Sierra Nevada mountains and the ocean from that town allowed him to develop an appreciation of both. He graduated from high school in 1972 and moved to Berkeley to attend the University of California the following fall.

After investigating a variety of "careers" he became disenchanted with academia briefly and quit. After working a number of jobs a travelling considerably, he returned to college and discovered the discipline of soil science. Two years later, in 1977, he graduated with a degree that field.

In October of 1977 he started work with the Soil Conservation Service as a soil mapper in New Mexico. This provided a great opportunity to see the reality of soils in "the field" as opposed to the textbooks or laboratory and was a great experience. New Mexico was a fantastic place to work such a job. Unfortunately, the job of mapping breeds many questions but provides little opportunity to answer them.

Because the university seemed to the place where such an opportunity might exist, he started graduate studies in the University of Florida in 1980. While studying soil genesis he discovered the research approach that those in

soil physics were taking. After obtaining his M. S. in 1982, he immediately flew to Costa Rica to apply this approach to many of the questions he had been asking since the old mapping days. This work has constituted a Ph.D. dissertation. Although many questions remain to be answered, the effort proved very satisfying.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

P. S. C. Rao, Chairman
Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

R. S. Mansell
Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

D. A. Graetz
Associate Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

N. B. Comerford
Associate Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

J. M. Bennett
Associate Professor of Agronomy

This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate School, and was accepted as partial fufillment of the requirements for the degree of Doctor of Philosophy.

August 1986

Dean, College of Agriculture

Dean, Graduate School

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